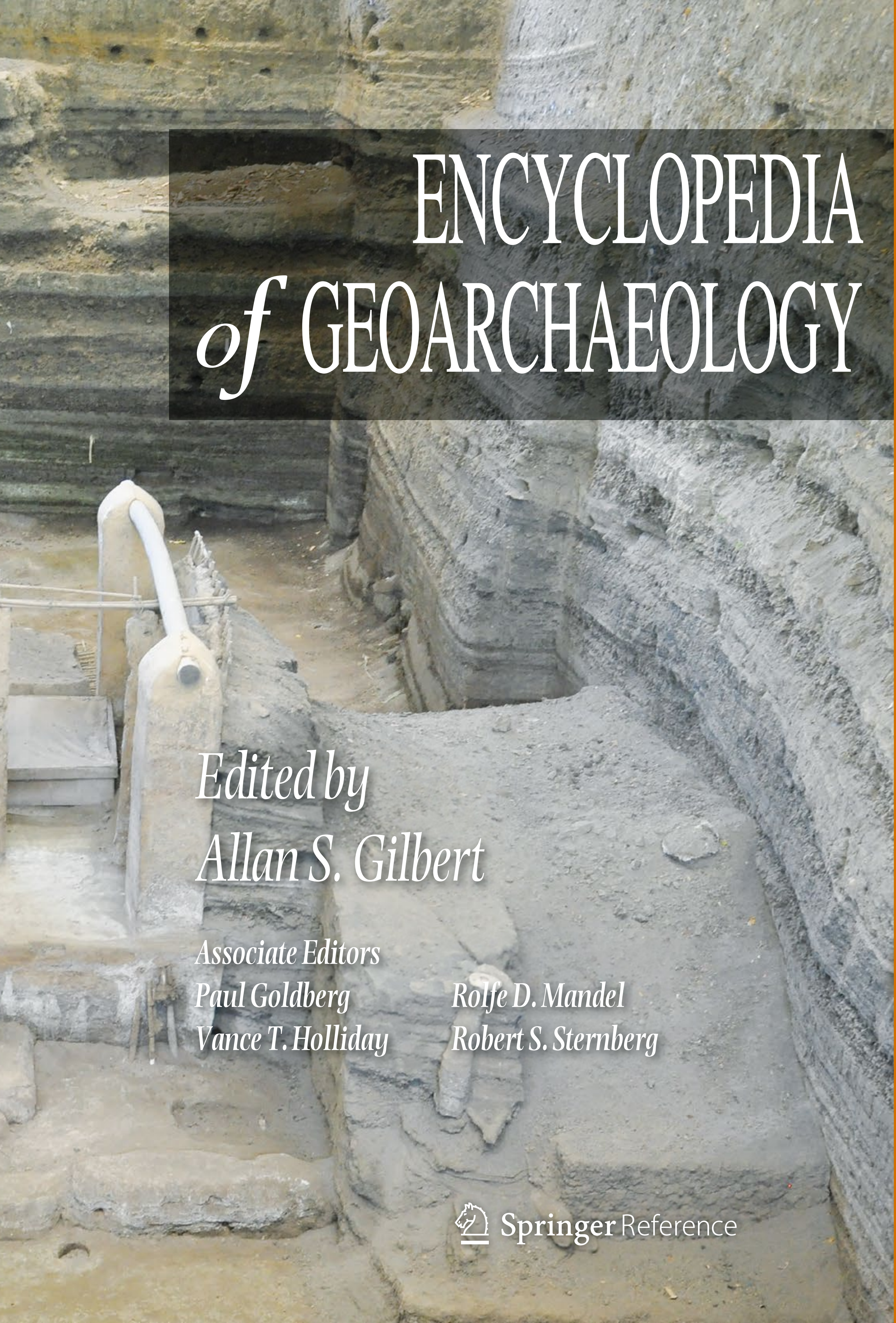


ENCYCLOPEDIA *of* GEOARCHAEOLOGY

Edited by
Allan S. Gilbert

Associate Editors
Paul Goldberg · *Rolfe D. Mandel*
Vance T. Holliday · *Robert S. Sternberg*

Springer Reference

ENCYCLOPEDIA *of* EARTH SCIENCES SERIES

ENCYCLOPEDIA *of* GEOARCHAEOLOGY

Encyclopedia of Earth Sciences Series

ENCYCLOPEDIA OF GEOARCHAEOLOGY

Volume Editor

Allan S. Gilbert is Professor of Anthropology at Fordham University in the Bronx, New York. He holds a B.A. from Rutgers University, and his M.A., M.Phil., and Ph.D. in anthropology were earned at Columbia University. His areas of research interest include the Near East (late prehistory and early historic periods) as well as the Middle Atlantic region of the USA. (historical archaeology). His specializations are in archaeozoology of the Near East and geoarchaeology, especially mineralogy and compositional analysis of pottery and building materials. Publications have covered a range of subjects, including ancient pastoralism, faunal quantification, skeletal microanatomy, brick geochemistry, and two co-edited volumes on the marine geology and geoarchaeology of the Black Sea basin.

Associate Editors

Paul Goldberg
Department of Archaeology
Emeritus at Boston University
675 Commonwealth Ave
Boston, MA 02215, USA
paulberg@bu.edu

Vance T. Holliday
Departments of Anthropology and Geosciences
University of Arizona
210030 Tucson, AZ 85721-0030, USA
vthollid@email.arizona.edu

Rolfe D. Mandel
Department of Anthropology
University of Kansas
1415 Jayhawk Blvd
622 Fraser Hall
Lawrence, KS 66045, USA
mandel@kgs.ku.edu

Robert S. Sternberg
Department of Geosciences
Franklin and Marshall College
3003 Lancaster, PA 17604-3003, USA
Rob.Sternberg@fandm.edu

Advisory Editors

Zenobia Jacobs
School of Environmental and Earth Sciences
University of Wollongong
Wollongong, NSW 2522, Australia

Panagiotis Karkanas
Ephoreia of Palaeoanthropology & Speleology of Southern Greece
Athens, Greece

Joseph Schuldenrein
Geoarchaeology Research Associates
Yonkers, NY, USA

Sarah C. Sherwood
University of the South
Sewanee, TN, USA

R.E. Taylor, Emeritus,
Department of Anthropology
University of California at Riverside, Riverside
CA, USA

Claudio Vita-Finzi
Natural History Museum
South Hill Park, London, UK

Jamie Woodward
Geography, School of Environment and Development
The University of Manchester, Manchester, UK

Aims of the Series

The Encyclopedia of Earth Sciences Series provides comprehensive and authoritative coverage of all the main areas in the Earth Sciences. Each volume comprises a focused and carefully chosen collection of contributions from leading names in the subject, with copious illustrations and reference lists. These books represent one of the world's leading resources for the Earth Sciences community. Previous volumes are being updated and new works published so that the volumes will continue to be essential reading for all professional earth scientists, geologists, geophysicists, climatologists, and oceanographers as well as for teachers and students. Go to http://link.springer.com to visit the "Encyclopedia of Earth Sciences Series" online.

About the Series Editor

Professor Charles W. Finkl has edited and/or contributed to more than eight volumes in the Encyclopedia of Earth Sciences Series. For the past 25 years he has been the Executive Director of the Coastal Education and Research Foundation and Editor-in-Chief of the international *Journal of Coastal Research*. In addition to these duties, he was Professor at Florida Atlantic University in Boca Raton, Florida, USA. He is a graduate of the University of Western Australia (Perth) and previously worked for a wholly owned Australian subsidiary of the International Nickel Company of Canada (INCO). During his career, he acquired field experience in Australia; the Caribbean; South America; SW Pacific islands; Southern Africa; Western Europe; and the Pacific Northwest, Midwest, and Southeast USA.

Founding Series Editor

Professor Rhodes W. Fairbridge (deceased) has edited more than 24 Encyclopedias in the Earth Sciences Series. During his career he has worked as a petroleum geologist in the Middle East, been a WW II intelligence officer in the SW Pacific, and led expeditions to the Sahara, Arctic Canada, Arctic Scandinavia, Brazil, and New Guinea. He was Emeritus Professor of Geology at Columbia University and was affiliated with the Goddard Institute for Space Studies.

ENCYCLOPEDIA OF EARTH SCIENCES SERIES

ENCYCLOPEDIA *of* GEOARCHAEOLOGY

edited by

ALLAN S. GILBERT
Fordham University, Bronx, NY, USA

With Associate Editors

PAUL GOLDBERG
Boston University, Boston, MA, USA

VANCE T. HOLLIDAY
University of Arizona, Tucson, AZ, USA

ROLFE D. MANDEL
University of Kansas, Lawrence, KS, USA

ROBERT S. STERNBERG
Franklin & Marshall College, Lancaster, PA, USA

Springer Reference

Library of Congress Control Number: 2016936270

ISBN: 978-94-007-4827-9
This publication is available also as:
Electronic publication under ISBN 978-1-4020-4409-0 and
Print and electronic bundle under ISBN 978-94-007-4828-6

Springer Dordrecht, Heidelberg, New York, London

Printed on acid-free paper

Cover photo: Photograph of Structure 4 at the Ceren archaeological site, El Salvador, which functioned as the bodega (storehouse) for Household 4 in an ancient Maya village. The village was buried by tephra from the nearby Loma Caldera volcanic vent in about AD 650. The various layers of the phreatomagmatic eruption resulted in extraordinarily good preservation of structures, including the thatch roofs, as well as the foods and artifacts stored within the buildings. Image courtesy of Payson Sheets, University of Colorado.

Dedicated to Rhodes W. Fairbridge

(1914–2006)
with appreciation

Contents

Editorial Board

Contributors

Katherine A. Adelsberger
Environmental Studies
Douglas and Maria Bayer Chair in Earth Science
Knox College
2 East South St.
Galesburg, IL 61401
USA
kadelsbe@knox.edu

J. M. Adovasio
Research Programs/Services
Florida Atlantic University–Harbor Branch
5600 US-1
Fort Pierce, FL 34946
USA
jadovasio@fau.edu

Nira Alperson-Afil
The Martin (Szusz) Department of Land of Israel Studies and Archaeology
Bar Ilan University
Ramat-Gan 5290002
Israel
nira.alperson-afil@biu.ac.il

Ruth Ann Armitage
Department of Chemistry
Eastern Michigan University
541 Science Complex
Ypsilanti, MI 48197
USA
rarmitage@emich.edu

Gilberto Artioli
Dipartimento di Geoscienze
Università degli Studi di Padova
Via Gradenigo 6
35131 Padova
Italy
gilberto.artioli@unipd.it

Gail M. Ashley
Department of Earth and Planetary Sciences
Rutgers University
Wright Geological Laboratory, Room 230
610 Taylor Road
Piscataway, NJ 08854
USA
gmashley@rci.rutgers.edu

Ian K. Bailiff
Department of Archaeology
University of Durham
South Road
Durham DH1 3LE
UK
ian.bailiff@durham.ac.uk

Timothy Beach
Department of Geography and the Environment
The University of Texas at Austin
305 E. 23rd Street CLA building, main office- CLA 3.306
Austin, TX 78712
USA
beacht@austin.utexas.edu

Francesco Berna
Department of Archaeology
Simon Fraser University
Education Bulding 9635, 8888 University Dr.
Burnaby, BC V5A 1S6
Canada
francesco_berna@sfu.ca

E. Arthur Bettis III
Department of Earth and Environmental Sciences
University of Iowa
Trowbridge Hall
Iowa City, IA 52242
USA
art-bettis@uiowa.edu

John Bintliff
School of Archaeology, Classics and History
Edinburgh University
4 Teviot Place
Edinburgh EH8 9AG
UK
johnlbintliff@gmail.com
j.l.bintliff@arch.leidenuniv.nl

Ronald L. Bishop
Department of Anthropology
National Museum of Natural History
Smithsonian Institution
37012 20013-7012 Washington, DC
USA
bishopr@si.edu

Giovanni Boschian
Dipartimento di Biologia
Università di Pisa
1, via Derna
56100 Pisa
Italy
giovanni.boschian@unipi.it

Jim Bowler
Earth Sciences
University of Melbourne
308 McCoy
Parkville Campus, VIC 3010
Australia
jbowler@unimelb.edu.au

James H. Burton
Department of Anthropology
University of Wisconsin
5240 W. H. Sewell Social Science Building
1180 Observatory Dr
Madison, WI 53706
USA
jhburton@wisc.edu

Stefano Campana
Faculty of Classics and McDonald Institute for Archaeological Research
University of Cambridge
Sidgwick Avenue
Cambridge CB3 9DA
UK
and
Laboratory of Landscape Archaeology and Remote Sensing, Department of History and Cultural Heritage
University of Siena
Via Roma 56
53100 Siena
Italy
srlc3@cam.ac.uk

Nicolas Carayon
Archéologie des Sociétés Méditerranéennes, UMR 5140
390 avenue de Pérols
34970 Lattes
France

Lawrence B. Conyers
Department of Anthropology
University of Denver
2000 E. Asbury St.
Denver, CO 80208
USA
lconyers@du.edu

Carlos E. Cordova
Department of Geography
Oklahoma State University
337 Murray Hall
Stillwater, OK 74078
USA
carlos.cordova@okstate.edu

Rinita A. Dalan
Department of Anthropology and Earth Science
Minnesota State University Moorhead
1104 7th Avenue South
Moorhead, MN 56563
USA
dalanri@mnstate.edu

Richard S. Davis
Department of Anthropology
Bryn Mawr College
Bryn Mawr, PA 19010-2899
USA
rdavis@brynmawr.edu

Erin C. Dempsey
National Park Service, Midwest Archeological Center
100 Centennial Mall North, Room 474
Lincoln, NE
68508 USA
erin_dempsey@nps.gov

Tim Denham
Archaeological Science Programs
School of Archaeology and Anthropology
The Australian National University
Canberra, ACT 0200
Australia
Tim.Denham@anu.edu.au

James H. Dickson
Dickson Laboratory for Bioarchaeology, York
Archaeological Trust
Kelvin Campus, 2317 Maryhill Road
Glasgow G20 OSP
UK
prof.j.h.dickson@gmail.com

Tom D. Dillehay
Department of Anthropology
Vanderbilt University
124 Garland Hall
Nashville, TN 37235
USA
tom.d.dillehay@vanderbilt.edu

Mathieu Duval
ESR Dating Laboratory, Geochronology
Centro Nacional de Investigación sobre la Evolución
Humana (CENIEH)
Paseo Sierra de Atapuerca, 3
09002 Burgos
Spain
mathieu.duval@cenieh.es

Jörg W. E. Fassbinder
Ludwig–Maximilians University of Munich
Theresienstraβe 4l
80333 Munich
Germany
and
Bayerisches Landesamt für Denkmalpflege
Hofgraben 4
80539 Munich
Germany
fassbinder@geophysik.uni-muenchen.de

Francesco G. Fedele
Formerly University of Naples 'Federico II'
Via Foligno 78/10
10149 Torino
Italy
fedele0@yahoo.it

C. Reid Ferring
Department of Geography
University of North Texas
1155 Union Circle #305279
Denton, TX 76203
USA
ferring@unt.edu

Erich C. Fisher
School of Human Evolution and Social Change
Arizona State University
Coor Hall, 5534
Tempe, AZ 85287-2402
USA
erich.fisher@asu.edu

Clément Flaux
Aix-Marseille Université, IUF, CEREGE UMR 6635
Europôle de l'Arbois, BP 80
13545 Aix-en-Provence cedex 04
France

Nic C. Flemming
National Oceanography Centre
University of Southampton
Waterfront Campus, European Way
Southampton, Hampshire SO14 3ZH
UK
nflemming@sheetsheath.co.uk

Ellery Frahm
Department of Anthropology
University of Minnesota-Twin Cities
HHH #395, 301 19th Ave S
Minneapolis, MN 55455
USA
frah0010@umn.edu

Andrea Freeman
Department of Anthropology and Archaeology and Earth Science Program
University of Calgary
Calgary, AB T2N 1N4
Canada
freeman@ucalgary.ca

Charles A. I. French
Department of Archaeology and Anthropology
University of Cambridge
1.3, West Building
Cambridge CB2 3DZ
UK
caif2@cam.ac.uk

Philip L. Gibbard
Cambridge Quaternary, Department of Geography
University of Cambridge
Downing Street
Cambridge CB2 3EN
UK
plg1@cam.ac.uk

Michael D. Glascock
Archaeometry Laboratory, Research Reactor Center
University of Missouri
1513 Research Park Dr
Columbia, MO 65211
USA
glascockm@missouri.edu

Paul Goldberg
Department of Archaeology
Emeritus at Boston University
675 Commonwealth Ave.
Boston, MA 02215
USA
paulberg@bu.edu

Manuel R. González Morales
Instituto Internacional de Investigaciones Prehistóricas
Universidad de Cantabria
Santander 39005
Spain
moralesm@unican.es

Beverly N. Goodman-Tchernov
Moshe Strauss Department of Marine Geosciences, Leon Charney School of Marine Sciences
University of Haifa
Mt. Carmel
Haifa 31905
Israel
bgoodman@univ.haifa.ac.il

Matthew R. Goodrum
Department of Science and Technology in Society
Virginia Tech
133 Lane Hall
Blacksburg, VA 24061
USA
mgoodrum@vt.edu

Andrew S. Goudie
School of Geography and the Environment
University of Oxford
South Parks Road
Oxford OX1 3QY
UK
andrew.goudie@stx.ox.ac.uk

Kelly E. Graf
Department of Anthropology
Texas A&M University
MS 4352
College Station, TX 77843-4352
USA
kgraf@tamu.edu

Michael W. Gregg
Department of Anthropology
St. Francis Xavier University
2320 Notre Dame Avenue
Antigonish, NS B2G2W5
Canada
greggmic@sas.upenn.edu

Magnus M. Haaland
Department of Archaeology
History Cultural Studies and Religion, University of Bergen
Øysteinsgate 3, Postboks
7805 5020 Bergen
Norway
Magnus.Haaland@ahkr.uib.no

Edwin R. Hajic
GeoArc Research, Inc.
55 Camino Cabo
Santa Fe, NM 87508
USA
hajic@geoarc.net

Jessi J. Halligan
Department of Anthropology
Florida State University
1847 West Tennessee St.
Tallahassee, FL 32308
USA
jessihalligan@tamu.edu

Edward Cecil Harris
National Museum of Bermuda
1 The Keep, Sandys Parish
MA 133 MABX Sandys
Bermuda
scaurbda@me.com

Christopher S. Henshilwood
Department of Archaeology, History
Cultural Studies and Religion, University of Bergen
Øysteinsgate 3, Postboks
7805 5020 Bergen
Norway
Christopher.Henshilwood@ahkr.uib.no

Christopher L. Hill
Graduate College
Boise State University
1910 University Drive
Boise, ID 83725-1950
USA
chill2@boisestate.edu

John F. Hoffecker
INSTAAR (Institute of Arctic and Alpine Research)
University of Colorado
1560 30th Street
Boulder, CO 80309-0450
USA
john.hoffecker@colorado.edu

Vance T. Holliday
Departments of Anthropology and Geosciences
University of Arizona
1009 E. South Campus Drive
Tucson, AZ 85721-0030
USA
vthollid@email.arizona.edu

Jeffrey A. Homburg
Statistical Research, Inc
P.O. Box 31865 Tucson, AZ 85751
USA
jhomburg@sricrm.com

Gary Huckleberry
Department of Geosciences
University of Arizona
Gould-Simpson Building, #77, 1040 E. 4th Street
Tucson, AZ 85721
USA
ghuck@email.arizona.edu

O. Frank Huffman
Department of Anthropology
University of Texas at Austin
Box 548 Bastrop, TX 78602
USA
huffmanof@mail.utexas.edu
huffmanof@austin.utexas.edu

Chris O. Hunt
School of Natural Sciences and Psychology
Liverpool John Moores University
Byrom Street
Liverpool L3 3LH
UK
C.O.Hunt@ljmu.ac.uk
c.hunt@qub.ac.uk

Kristin Ismail-Meyer
Department of Environmental Sciences
Integrative Prehistory and Archaeological Science (IPAS)
University of Basel
Spalenring 145
4055 Basel
Switzerland
Kristin.Meyer@unibas.ch

Zenobia Jacobs
School of Environmental and Earth Sciences
University of Wollongong
Northfields Avenue
Wollongong, NSW 2522
Australia
zenobia@uow.edu.au

Panagiotis Karkanas
Ephoreia of Palaeoanthropology-Speleology of
Southern Greece
Ardittou 34b
11636 Athens
Greece
pkarkanas@hua.gr

Henk Kars
Geo- and Bioarchaeology
Faculty of Earth and Life Sciences
VU University
De Boelelaan 1085
1081 HV Amsterdam
The Netherlands
h.kars@vu.nl

Barry Kohn
School of Earth Sciences
University of Melbourne
McCoy Building
Melbourne, VIC 3010
Australia
b.kohn@unimelb.edu.au

Charles C. Kolb
1005 Pruitt Court, SW
Vienna, VA 22180–6429
USA
and
National Endowment for the Humanities
Washington, DC 20506
USA
CCKolb.13@gmail.com
CKolb@neh.gov

Michael F. Kolb
Strata Morph Geoexploration, Inc
1648 Calico Court
53590 Sun Prairie, WI
USA
mikekolb@charter.net

Jan D. Kramers
Department of Geology
University of Johannesburg, Auckland Park Kingsway Campus
Auckland Park 2006 Johannesburg
South Africa
jkramers@uj.ac.za

Kenneth L. Kvamme
Department of Anthropology
University of Arkansas
Fayetteville, AR 72701
USA
kkvamme@uark.edu

Jonathan G. A. Lageard
Division of Geography and Environmental Management
School of Science and the Environment
Faculty of Science and Engineering
Manchester Metropolitan University
Chester Street
Manchester M1 5GD
UK
j.a.lageard@mmu.ac.uk

Christine Lane
Geography, School of Environment
Education and Development
The University of Manchester
Manchester M13 9PL
UK
christine.lane@manchester.ac.uk

Alfred G. Latham
Archaeology, Classics and Egyptology
Liverpool University
Liverpool L69 3GS
UK
aa09@liv.ac.uk

Stacey Lengyel
Illinois State Museum
1011 E. Ash St.
Springfield, IL 62703
USA
slengyel@museum.state.il.us

Gloria I. López
Luminescence Laboratory
Centro Nacional de Investigación sobre la Evolución Humana CENIEH
Paseo Sierra Atapuerca, 3
Burgos 09002
Spain
and
Leon Recanati Institute for Maritime Studies
University of Haifa, Mt. Carmel
Haifa 31905
Israel
lopezgi.phd@gmail.com

Richard I. Macphail
Institute of Archaeology
University College London
31-34 Gordon Square
London WC1H OPY
UK
r.macphail@ucl.ac.uk

Michel Magny
CNRS, UMR 6249
CNRS, Laboratoire Chrono-Environnement
Besançon
France
Michel.Magny@univ-fcomte.fr

Carolina Mallol
Departamento de Geografía e Historia
Universidad de La Laguna
Campus de Guajara, La Laguna
38071 Tenerife
Spain
cmallol@ull.es
carolina.mallol@gmail.com

Rolfe D. Mandel
Department of Anthropology
University of Kansas
1415 Jayhawk Blvd
622 Fraser Hall
Lawrence, KS 66045
USA
mandel@kgs.ku.edu

Curtis W. Marean
Institute of Human Origins
School of Human Evolution and Social Change
PO Box 872402, Arizona State University
Tempe, AZ 85287–2402
USA
and
Centre for Coastal Palaeoscience
Nelson Mandela Metropolitan University
Port Elizabeth, Eastern Cape 6031
South Africa
Curtis.Marean@asu.edu

Nick Marriner
CNRS, Laboratoire Chrono-Environnement UMR 6249
Université de Franche-Comté
UFR ST, 16 route de Gray
25030 Besançon
France
nick.marriner@univ-fcomte.fr
marriner@cerege.fr

Ari Matmon
The Institute of Earth Sciences
The Hebrew University
Edmond J. Safra campus, Givat Ram
Jerusalem 91904
Israel
arimatmon@cc.huji.ac.il

Wendy Matthews
Department of Archaeology, School of Archaeology
Geography and Environmental Science
University of Reading
Reading
UK
w.matthews@reading.ac.uk

Floyd W. McCoy
Department of Natural Sciences
University of Hawaii – Windward
45-720 Kea'ahala Road
Kane'ohe, HI 96744
USA
fmccoy@hawaii.edu

Susan M. Mentzer
Institute for Archaeological Sciences
University of Tübingen
Rümelinstr. 23
72070
Germany
and
School of Anthropology
University of Arizona
Tucson, AZ, 72070
USA
susan.mentzer@ifu.uni-tuebingen.de

Christopher E. Miller
Institute for Archaeological Sciences, Senckenberg Centre for Human Evolution and Paleoenvironment
University of Tübingen
Rümelinstr. 23
72070 Tübingen
Germany
christopher.miller@uni-tuebingen.de

Leah E. Morgan
Scottish Universities Environmental Research Centre
G75 0QF East Kilbride
UK
leahetgmorgan@gmail.com

Christophe Morhange
CNRS CEREGE, UMR 6635
Aix-Marseille University
Aix-en-Provence
France
morhange@cerege.fr

Maru Mormina
Department of Applied Social Studies
University of Winchester
Sparkford Road
Winchester SO22 4NR
UK
Maru.Mormina@winchester.ac.uk

Hector Neff
Department of Anthropology and IIRMES
California State University Long Beach
1250 Bellflower Blvd
Long Beach, CA 90840
USA
hector.neff@csulb.edu

Tina M. Niemi
Department of Geosciences
University of Missouri-Kansas City
Kansas City, MO 64110
USA
niemit@umkc.edu

Lee C. Nordt
Department of Geology
Baylor University
Waco, TX 76798
USA
lee_nordt@baylor.edu

Patrick D. Nunn
Australian Centre for Pacific Islands Research
The University of the Sunshine Coast
Maroochydore, QLD 4558
Australia
pnunn@usc.edu.au

Charles R. Ortloff
Research Associate
University of Chicago
CFD Consultants Int'l, Ltd.
18310 Southview Avenue
Los Gatos, CA 95033-8537
USA
ortloff5@aol.com

Anthony L. Ortmann
Department of Geosciences
Murray State University
Murray, KY 42071
USA
aortmann@murraystate.edu

J. Victor Owen
Department of Geology
Saint Mary's University
B3H 3C3 Halifax, NS
Canada
victor.owen@smu.ca

Josep M. Parés
Geochronology Program
CENIEH
Paseo Sierra de Atapuerca 3
09902 Burgos
Spain
Josep.pares@cenieh.es

Mike Parker Pearson
Institute of Archaeology
University College London
31-34 Gordon Square
London WC1H 0PY
UK
m.parker-pearson@ucl.ac.uk

Kirsty Penkman
BioArCh, Department of Chemistry
University of York
York YO10 5DD
UK
kirsty.penkman@york.ac.uk

Robyn Pickering
School of Earth Sciences
University of Melbourne
McCoy Building
Parkville, Victoria 3010
Australia
r.pickering@unimelb.edu.au

Dennis Piechota
Department of Anthropology
Fiske Center for Archaeological Research
University of Massachusetts at Boston
100 Morrissey Blvd.
Boston, MA 02125
USA
dennis.piechota@umb.edu

A. Mark Pollard
Research Laboratory for Archaeology and the History of Art, School of Archaeology
University of Oxford
Dyson Perrins Building South Parks Road
Oxford
UK
mark.pollard@rlaha.ox.ac.uk

Ben A. Potter
Department of Anthropology
University of Alaska Fairbanks
Fairbanks, AK 99775
USA
bapotter@alaska.edu

Rory Quinn
Centre for Maritime Archaeology
School of Environmental Sciences
University of Ulster
BT52 1SA Coleraine
Northern Ireland, UK
RJ.Quinn@ulster.ac.uk

George Rip Rapp
Department of Geological Sciences
University of Minnesota
Duluth and Minneapolis Campuses, University Drive
Duluth, MN 55812
USA
grapp@d.umn.edu

Philippe Rentzel
Department of Environmental Sciences
Integrative Prehistory and Archaeological Science (IPAS)
University of Basel
Spalenring 145
4055 Basel
Switzerland
Philippe.Rentzel@unibas.ch

Joshua D. Reuther
University of Alaska Museum of the North
Fairbanks, AK 99775
USA
and
Department of Anthropology
University of Alaska Fairbanks
Fairbanks, AK 99775
USA
jreuther@alaska.edu

Daniel Richter
Department of Geography
Geographisches Institut University of Bayreuth
Universitätsstrasse 30
95447 Bayreuth
Germany
and
Department of Human Evolution
Max Planck Institute for Evolutionary Anthropology
Leipzig
Germany
drichter@eva.mpg.de

Charlotte A. Roberts
Department of Archaeology
Durham University
South Road
Durham DH1 3LE
UK
c.a.roberts@durham.ac.uk

Neil Roberts
School of Geography, Earth and Environmental Sciences
Faculty of Science and Environment
Plymouth University
PL4 8AA Plymouth, Devon
UK
C.N.Roberts@plymouth.ac.uk

Jonathan A. Sandor
Agronomy Department
Iowa State University
P.O. Box 1994 Corrales, NM 87048
USA
jasandor@iastate.edu

Apostolos Sarris
Laboratory of Geophysical-Satellite Remote Sensing and Archaeo-environment
Foundation for Research and Technology, Hellas (F.O.R.T.H.), Institute for Mediterranean Studies (I.M.S.)
Melissinou & Nik. Foka 130
PO. Box 119 Rethymnon 74100 Crete
Greece
asaris@ret.forthnet.gr
asaris@ims.forth.gr

Vernon L. Scarborough
Department of Anthropology
University of Cincinnati
Cincinnati, OH 45221-0380
USA
vernon.scarborough@uc.edu

Joseph Schuldenrein
Geoarchaeology Research Associates
5912 Spencer Avenue
Bronx, NY 10471
USA
joseph.schuldenrein@gra-geoarch.com

Judith Sealy
Department of Archaeology
University of Cape Town
Private Bag X3
7701 Rondebosch, Cape Town
South Africa
Judith.Sealy@uct.ac.za

Maria Rosaria Senatore
Dipartimento di Scienze e Tecnologie
Università degli Studi del Sannio
Via dei Mulini, 59/A
Benevento 82100
Italy
senatore@unisannio.it

Vincent Serneels
Department Geosciences
University Fribourg
Chemin du Musée 6 – Pérolles
1700 Fribourg
Switzerland
Vincent.serneels@unifr.ch

M. Steven Shackley
Geoarchaeological XRF Laboratory
Department of Anthropology
University of California
232 Kroeber Hall
Berkeley, CA 94720-3710
USA
shackley@berkeley.edu

Payson Sheets
Department of Anthropology
University of Colorado
80309-0233 Boulder, CO
USA
payson.sheets@colorado.edu

Chen Shen
Royal Ontario Museum
100 Queen's Park
M5S 2C6 Toronto, ON
Canada
chens@rom.on.ca
chen.shen@utoronto.ca

Sarah C. Sherwood
Environmental Studies
The University of the South
735 University Ave
Sewanee, TN 37383
USA
sherwood@sewanee.edu

John F. Shroder
Department of Geography and Geology
University of Nebraska at Omaha
Omaha, NE 68182
USA
jshroder@mail.unomaha.edu

Alan H. Simmons
Department of Anthropology
University of Nevada Las Vegas
4505 S. Maryland Parkway
POB 455003 Las Vegas, NV 89154
USA
alan.simmons@unlv.edu
simmonsa@unlv.nevada.edu

Julie K. Stein
Burke Museum of Natural History and Culture
University of Washington
Box 35-3010 Seattle, WA 98195-3010
USA
jkstein@u.washington.edu

Dominic Stratford
School of Geography
Archaeology and Environmental Studies
University of the Witwatersrand
Witwatersrand, Johannesburg
South Africa
and
Sterkfontein Caves Palaeoanthropological Site
Johannesburg
South Africa
Dominic.Stratford@wits.ac.za

Lawrence Guy Straus
Department of Anthropology
University of New Mexico
Albuquerque, NM 87131–0001
USA
and
Instituto Internacional de Investigaciones Prehistóricas
Universidad de Cantabria
Santander 39005
Spain
lstraus@unm.edu

Linea Sundstrom
Principal, Day Star Research
1320 E Lake Bluff Blvd.
Shorewood, WI 53211
USA
linea.sundstrom@gmail.com

Jiří Svoboda
Insitute of Archaeology
Academy of Sciences of the Czech Republic
69129 Dolní Věstonice
Czech Republic
and
Department of Anthropology, Faculty of Science
Masaryk University
Kotlářská 2
600 00 Brno
Czech Republic
jsvoboda@sci.muni.cz

Katherine Szabó
Centre for Archaeological Science
School of Earth and Environmental Sciences
University of Wollongong
Northfields Avenue
Wollongong 2522 NSW
Australia
kat@uow.edu.au

Alain Tabbagh
Université Pierre et Marie Curie
UMR 7619 Métis, 4, place Jussieu
75252, cedex 05 Paris
France
alain.tabbagh@upmc.fr

Kenneth B. Tankersley
Department of Anthropology and Department of Geology
University of Cincinnati
Cincinnati, OH 45221-0380
USA
tankerkh@uc.edu

R. E. Taylor
Emeritus, Department of Anthropology
University of California, Riverside
1334 Watkins Hall
Riverside, CA 92521-0418
USA
ervin.taylor@ucr.edu

Richard E. Terry
Plant and Wildlife Sciences Department
Brigham Young University
4105 Life Sciences Building
Provo, UT 84602
USA
richard_terry@byu.edu

Alston V. Thoms
Department of Anthropology
Texas A&M University
College Station, TX 77843-4352
USA
a-thoms@tamu.edu

Georgia Tsartsidou
Ephoreia of Palaeoanthropology-Speleology
Ardittou 34 B
116 36 Athens
Greece
gtsartsidou@ymail.com

Maria-Raimonda Usai
Dipartimento di Architettura, Design e Urbanistica
Università di Sassari
Piazza Duomo 6 (via Manno)
07041 Alghero (SS)
Italy
mariaraimonda.usai@gmail.com

Claudio Vita-Finzi
Natural History Museum
22 South Hill Park
London, NW 32SB
UK
cvitafinzi@aol.com

Daniel P. Wagner
Geo-Sci Consultants LLC
4410 Van Buren Street
20782 University Park, MD
USA
danwagner@juno.com

Ian Watts
20 Aristophanous
10554 Athens
Greece
ochrewatts@hotmail.com

Brandon J. Weihs
Department of Geography
Kansas State University
Manhattan, KS
USA
bweihs@k-state.edu

Kira E. Westaway
Department of Environmental Sciences
Macquarie University
E7A632, Eastern Avenue
North Ryde, NSW 2109
Australia
kira.westaway@mq.edu.au

Ian K. Whitbread
School of Archaeology and Ancient History
University of Leicester
University Road
Leicester LE1 7RH
UK
ikw3@le.ac.uk

Tom S. White
Research Laboratory for Archaeology and the History of Art
University of Oxford
Hayes House, 75 George Street
Oxford OX1 2BQ
UK
tom.white@rlaha.ox.ac.uk

Jamie Woodward
Geography, School of Environment
Education and Development
The University of Manchester
Manchester M13 9PL
UK
jamie.woodward@manchester.ac.uk

Lori E. Wright
Department of Anthropology
Texas A&M University
College Station, TX 77843-4352
USA
lwright@tamu.edu

Marcelo A. Zárate
INCITAP (Institute of Earth and Environmental Sciences of La Pampa)
CONICET/National University of La Pampa
Avenida Uruguay 151
6300 Santa Rosa, La Pampa
Argentina
mzarate@exactas.unlpam.edu.ar
marcelozarate55@yahoo.com.ar

Preface

"Geoarchaeology" is the archaeological subfield that uses the methods of geological investigation to gather information and solve problems in the exploration of the human past. Under the label of "archaeological geology," it is also the subfield of geology that explores geoscience aspects of human antiquity. In its varied manifestations, then, geoarchaeological research attempts to build collaborative links between specialists in archaeology and the Earth sciences and, in so doing, produce new knowledge about past human behavior by merging methods and concepts from the geosciences with those commonly applied by archaeologists.

Archaeological recovery and analysis are already geoarchaeological in the most fundamental sense because the buried remains left by former humans are contained within, and removed from, an essentially geological context, and many of the finds are themselves composed of earthen or rock materials. But geoarchaeology moves beyond this simple relationship to pursue a broad range of questions, many of which address the interactions and influences between humans and the environments in which they once lived. The proximate goals of geoarchaeology might be described as elucidating the processes of site formation, reconstructing ancient environments and the influence of humans on them at the local and regional levels, and learning which environmental factors were significant in the evolutionary emergence of humankind and the cultural changes undergone by the world's diverse societies over time. Tactically, the toolkit of research techniques, conducted in both field and laboratory contexts, includes analyses of soils, sediments, rocks, and landforms, and a wide range of geophysical, geochemical, and microscopic methods. At a finer scale of resolution, for example, the study of archaeological deposits to infer past human activities and behaviors – such as agriculture, pastoralism, and fire – lies firmly within the scope of geoarchaeology. There is an overlap of geoarchaeological methods covered in this work with techniques also considered to be part of archaeometry: materials analysis, dating, methods of site location and prospecting, and tracing raw and artifactual materials to their sources. The ultimate goal, like many other subfields of archaeology, is the recovery of new information that would permit fresh and more detailed interpretations of human antiquity.

Early studies of the natural world in Europe and America during the eighteenth and nineteenth centuries often included a concern for humans and their place in nature. Much initial prehistoric research in both hemispheres was in fact conducted by geologists, who took an interest in the remains of human activities (and the remains of humans themselves) deposited along with geological materials. In the 1950s and 1960s, a greater emphasis on environmental factors in archaeology led eventually to a "contextual approach" involving "geoarchaeological" investigations proposed by Karl Butzer in the 1970s. The subfield is therefore relatively young compared to archaeology and the geosciences in general. Yet, for archaeologists, the specialized preparation needed in order to understand the geological complexities of their research has made geoarchaeology relatively inaccessible to many. Most geoarchaeologists working today have had some interdisciplinary training in the Earth sciences, or their degrees were earned wholly in the geosciences. Such credentials are necessary for those exploring prehistoric periods, as they must acquire the expertise to obtain accurate dating of sites and finds, understand the depositional history of a site and its contents over long intervals, and reconstruct paleoenvironmental conditions to interpret ancient lifeways in their original settings. Archaeometric research holds a significant place in the archaeology of historical periods, but with some exceptions, field geoarchaeological practice and familiarity with its methods and knowledge base tend to be lesser components of archaeological research conducted on recent cultures and sites. New World historical archaeology tends to place little emphasis on geoarchaeological matters, while the archaeology of Roman and later periods in Europe is more likely to use it in the analysis of sites.

The potential benefit of geoarchaeological applications to all archaeological investigations has prompted the present volume. While specialized treatises on geoarchaeology began to appear in the 1960s and 1970s, it was Rhodes Fairbridge, founding editor of the Earth Science Encyclopedia Series (EEES), who proposed that an encyclopedic work on geoarchaeology be added to the list of published volumes. He enlisted a newly minted Ph.D. in Anthropology at Columbia University, Allan Gilbert, to help with the project, and the first publication contract was signed in 1981. The geoarchaeological landscape 35 years ago was distinctly incipient, with but a limited number of active practitioners engaged in research and publication, and a small body of basic knowledge that had already accumulated. Had that volume been realized, it would have been restricted to only the few geoarchaeological projects and subject areas that had been explored at the time, and much of the rest would have comprised entries on archaeological or geological topics. Sadly, but perhaps luckily, the contract was cancelled in the mid-1980s due to a change in publishers and a realignment of priorities at the new publishing house. The volume then began a lengthy search for a new agreement elsewhere. It did not find solid grounding with a new publisher until Springer offered to contract the project in 2002. Fairbridge passed away in 2006, and in the subsequent years Gilbert enlisted the assistance of four established geoarchaeologists (Paul Goldberg, Vance Holliday, Rolfe Mandel, and Rob Sternberg) to serve as associate editors and help assemble a new entry list that incorporated the advances and discoveries made within the subfield over the preceding two and a half decades. This volume is dedicated to the memory of Rhodes Fairbridge, whose appreciation for archaeology's contributions to Quaternary geoscience prompted his insistence that a reference work on geoarchaeology belonged within the stable of volumes he guided into print over his 40 years of editing the EEES.

This encyclopedia, appearing so many years after its initial conceptualization, contains data and discussion from a far wider range of practicing geoarchaeologists working within a far more mature discipline than would have been the case at its inception. It defines terms, introduces problems, describes techniques, and discusses theory and strategy, all in a language designed to make specialized details accessible to students and nonspecialists. It covers subjects in environmental archaeology, dating, prospection, materials analysis, soil and sediment investigation, and landforms, among other matters, and it includes a sampling of the most important sites known for their geoarchaeological contributions. The volume does not cover sites, civilizations, and ancient cultures that are less germane to the geoarchaeological focus and better described in other encyclopedias of world archaeology.

As mature as geoarchaeology has become, it is still a young and dynamic area of research. New applications are constantly emerging as the results of novel investigative techniques fill the pages of professional journals (notably *Geoarchaeology, An International Journal*; *Archaeological and Anthropological Sciences*; *Journal of Archaeological Science*; and *Archaeometry*), and as geoarchaeological approaches are aimed at different archaeological problems in different parts of the world. Original insights emanating from such developments will inevitably require revisions of this volume to keep up with progress, and coupled with the fact that lacunae remain in this book and will always exist in any comprehensive compilation, the *Encyclopedia of Geoarchaeology* will doubtless grow in detail and inclusiveness once this first edition appears. We look forward to constructive suggestions from readers about what is missing or in need of updating, as no editorial supervision will ever control the enormous diversity of innovation that will surely characterize the near future of geoarchaeology.

Allan S. Gilbert
Paul Goldberg
Vance T. Holliday
Rolfe D. Mandel
Robert S. Sternberg

Acknowledgments

The editors wish to thank all the contributors for dedicating time to participate in this project, especially those who were prompt with their entry submission, then waited patiently while the lengthy editorial process steadily took its course.

Together with the support received from the advisory board, we obtained additional help from various persons in the course of volume preparation, and to these we express gratitude: Bruce Bevan, Jim Burton, Jim Dickson, Robert Folk, Charly French, Angelina Guarino, Gary Huckleberry, Rich Macphail, Patrick McGovern, Laura Murphy, Paul Renne, and Steven Shackley. Whether the help was substantial or slight, we value the counsel and effort that was given, and apologize to those we may have inadvertently left off the list.

Appreciation is offered to Payson Sheets for kindly providing the cover photograph depicting volcanic sediments covering the Mesoamerican site of Cerén.

Editing assistance was provided by Suanna Selby Crowley. Graphics contributions were made by Tony Layzell and Mark Schoneweis.

Franklin & Marshall College provided two semesters of sabbatical leave to Rob Sternberg enabling him to conduct much of his editorial activities.

Finally, we extend thanks to our editors at Springer (Petra van Steenbergen, Sylvia Blago, and Simone Giesler), as well as the successive editors of the Earth Science Encyclopedia Series (Rhodes Fairbridge and Charlie Finkl), the first who initiated plans for the present volume, and the second who encouraged and followed the project to its completion.

Allan S. Gilbert
Paul Goldberg
Vance T. Holliday
Rolfe D. Mandel
Robert S. Sternberg

A

'AIN GHAZAL

Rolfe D. Mandel[1] and Alan H. Simmons[2]
[1]Department of Anthropology, University of Kansas, Lawrence, KS, USA
[2]Department of Anthropology, University of Nevada Las Vegas, Las Vegas, NV, USA

Definition

'Ain Ghazal ("Spring of the Gazelles") is a major Neolithic settlement located near Amman in northwestern Jordan. The site is situated on footslopes and toeslopes in the Zarqa River valley, the second largest tributary of the Jordan River. Archaeological excavations were conducted at 'Ain Ghazal during seasons beginning in 1982. Although a relatively small portion of the site has been excavated, the findings have been remarkable and have brought about the reevaluation of some basic assumptions regarding Neolithic life (Simmons, 2007). The most significant discoveries at the site relate to chronology, size and population, economy, ritual and artistic life, ecological adaptation, and the ultimate abandonment of the site.

Covering an area of at least 12 ha, 'Ain Ghazal is three times the size of Jericho and represents one of the largest aceramic Neolithic sites recorded in the Near East. Hence, it probably was a major population center, although the entire site may not have been occupied at the same time. At its peak, 'Ain Ghazal probably had a population of several thousand people, but after 8,500 cal years BP, the population dropped sharply.

Based on a large suite of radiocarbon ages, a major occupation occurred at 'Ain Ghazal between ca. 10,200 and 8,000 cal years BP, which corresponds to the Pre-Pottery Neolithic B (PPNB) (Simmons et al., 1988). There also was an occupation during the succeeding Pre-Pottery Neolithic C, and the site continued to be occupied into the Pottery Neolithic component, locally known as the Yarmoukian (Rollefson, 1993). The Yarmoukian component at 'Ain Ghazal dates to ca. 7,700 cal years BP (Kafafi et al., 2012: 27). In addition, Chalcolithic pastoralists appear to have occupied the site during two brief intervals around 7,200 and 6,500 cal years BP (Zielhofer et al., 2012). Aceramic and ceramic components often occur at major Neolithic sites, but they are often separated by a hiatus in the period of occupation. This is not the case at 'Ain Ghazal; a transitional phase from aceramic to ceramic was documented, the aforementioned Pre-Pottery Neolithic C (PPNC) (Simmons et al., 1988). The PPNC component shares elements common to both the PPNB and Yarmoukian, yet it is unique in many ways.

The recovery of abundant faunal and floral remains at 'Ain Ghazal provided a wealth of information about subsistence strategies during the periods of occupation. Goats dominate the faunal assemblage and, along with cattle, were used in a domestic sense (Köhler-Rollefson et al., 1988), although they may not have been morphologically domestic (Simmons et al., 1988). Also, a remarkable variety of wild animals were consumed at the site during the PPNB, with over 50 taxa identified in the assemblage, although by the second half of the 8th millennium, the wild component drops dramatically (von den Driesch and Wodtke, 1997). Gazelle, pig, hare, fox, and turtles are especially abundant. Plant foods appear to be dominated by legumes (primarily peas and lentils), though wheat, barley, chickpea, fig, and a wide variety of wild plants also were consumed (Donaldson, 1984; Neef, 2004).

'Ain Ghazal contains remarkably sophisticated and well-preserved architecture. During the Middle PPNB, housing consisted mostly of two-roomed rectangular dwellings with walls made of stones set in mud mortar. The interior faces of the structures were covered with

A.S. Gilbert (ed.), *Encyclopedia of Geoarchaeology*, DOI 10.1007/978-1-4020-4409-0,

mud plaster and coated with a thin layer of fine plaster, often decorated with red ochre. Floors were made of a high-quality plaster burnished to a high gloss and usually painted with red ochre. Sunken plastered hearths occur in the main living quarters, and often second rooms appear to have functioned as storage and food-processing areas. Wooden posts ran up some of the walls and from central portions of the floors to support the roof.

The most spectacular discovery at the site was two caches of human statues and busts in the Middle PPNB levels. The statues are 80–100 cm tall and consist of high-quality white plaster around a core of bundled reeds; the busts also are made of plaster. In all, 32 plaster figures were recovered, 15 full figures, 15 busts, and two fragmentary heads. The statues have painted clothes, hair, and, in some cases, ornamental tattoos or body paint. The alignment of the statues in two tiers and the arrangement of the busts in an arc at the feet of the statues point to ritual behavior at 'Ain Ghazal.

Additional ritual behavior at 'Ain Ghazal is evidenced by smaller clay figures, including numerous human and animal figurines. Also, the treatment of the dead is strongly ritualistic. In most cases, the deceased individual was placed in a flexed position beneath the floor of a dwelling, and the burial pit was then plastered over. Sometime later, the burial was exhumed and the skull was removed. The location of most of the detached skulls is unknown; only a few caches of 13 skulls with evidence of plaster have been recovered (cf. Bonogofsky, 2001).

Clearly, the Middle and Late PPNB was a period of prosperity at 'Ain Ghazal, as indicated by the presence of a rich variety of domestic and wild animal and plant resources, an unprecedented level of artistic achievement, numerous animal and human figurines, remarkable statuary, and highly evolved ritual behavior (Rollefson and Simmons, 1987; Simmons et al., 1988). Also, sophisticated architecture evolved during this period, and during the Late PPNB, virtual "apartment houses" were constructed to house up to three to four families (Rollefson, 1997). However, perhaps as early as the PPNC, and certainly by the Yarmoukian, a dramatic shift in the subsistence strategy occurred that led to the abandonment of the site (Köhler-Rollefson and Rollefson, 1990). From heavy reliance on domesticated plants and animals, but supplemented by wild resources, the economy changed to one that relied on pastoralism, with goats or sheep (or both) becoming the primary food source (Simmons et al., 1988). The areal extent of 'Ain Ghazal decreased significantly during the Yarmoukian, and the archaeological record suggests that the village became impoverished and may have been occupied on a seasonal basis.

The results of a geoarchaeological investigation at 'Ain Ghazal indicate that the landscape became unstable toward the end of the PPNB and especially during the PPNC and Yarmoukian periods (Mandel and Simmons, 1988). Also, there is evidence for increased aridity during these periods (Zielhofer et al., 2012). Erosion was stripping soil off the steep sideslopes above the site, and sheetwash was depositing the "soil sediment" on the footslopes and toeslopes, resulting in burial of successive occupations. So what drove the landscape instability? At 'Ain Ghazal, it is likely that nonirrigated cultivation and animal husbandry initially were complementary subsistence strategies before a critical population size was reached and before the local environment began to deteriorate (Simmons et al., 1988). As the economy shifted to a strong dependence on goats and sheep, it is likely that overgrazing affected the fragile environment and accelerated soil erosion. Degradation of the environment would have forced the inhabitants of 'Ain Ghazal to move their goat herds farther and farther away. In sum, the environmental degradation caused by over 3,000 years of intensive land use during the Neolithic, combined with aridification, may have rendered the landscape surrounding 'Ain Ghazal incapable of supporting a major agriculturally based community, leading to the abandonment of the site around 7,000 years ago.

Bibliography

Bonogofsky, M. A., 2001. *An Osteo-Archaeological Examination of the Ancestor Cult during the Pre-Pottery Neolithic B Period in the Levant*. PhD dissertation, University of California, Berkeley. Ann Arbor: University Microfilms International.

Donaldson, M., 1984. *Preliminary Analysis of Plant Remains from the 1983 'Ain Ghazal Excavations*. Albuquerque: University of New Mexico. Castetter Laboratory for Ethnobotanical Studies, Technical Series, 118.

Kafafi, Z., Rollefson, G., Douglas, K., and Lash, A., 2012. 'Ain Ghazal revisited: rescue excavations, October and December–January, 2011–2012. *Neo-Lithics*, **2**(12), 21–29.

Köhler-Rollefson, I., and Rollefson, G. O., 1990. The impact of Neolithic subsistence strategies on the environment: the case of 'Ain Ghazal, Jordan. In Bottema, S., Entjes-Nieborg, G., and van Zeist, W. (eds.), *Man's Role in the Shaping of the Eastern Mediterranean Landscape*. Rotterdam: Balkema, pp. 3–14.

Köhler-Rollefson, I., Gillespie, W., and Metzger, M., 1988. The fauna from Neolithic 'Ain Ghazal. In Garrard, A. N., and Gebel, H. G. (eds.), *The Prehistory of Jordan: The State of Research in 1986*. Oxford: British Archaeological Reports. British Archaeological Reports International Series, 396, Vol. 2, pp. 423–430.

Mandel, R. D., and Simmons, A. H., 1988. A preliminary assessment of the geomorphology of 'Ain Ghazal. In Garrard, A. N., and Gebel, H. G. (eds.), *The Prehistory of Jordan: The State of Research in 1986*. Oxford: British Archaeological Reports. British Archaeological Reports International Series, 396, Vol. 2, pp. 431–436.

Neef, R., 2004. Vegetation and climate. A comparison between PPNB 'Ain Ghazal and Basta. In Bienert, H.-D., Gebel, H. G. K., and Neef, R. (eds.), *Central Settlements in Neolithic Jordan*. Berlin: Ex Oriente. Studies in Early Near Eastern Production, Subsistence, and Environment, 5, pp. 289–299.

Rollefson, G. O., 1993. The origins of the Yarmoukian at 'Ain Ghazal. *Paléorient*, **19**(1), 91–100.

Rollefson, G., 1997. Changes in architecture and social organization at 'Ain Ghazal. In Gebel, H. G., Kafafi, Z., and Rollefson, G. O. (eds.), *The Prehistory of Jordan. II. Perspectives from 1997*. Berlin: Ex Oriente. Studies in Early Near Eastern Production, Subsistence, and Environment, 4, pp. 287–307.

Rollefson, G. O., and Simmons, A. H., 1987. The life and death of 'Ain Ghazal. *Archaeology*, **40**(6), 38–45.

Simmons, A. H., 2007. *The Neolithic Revolution in the Near East: Transforming the Human Landscape*. Tucson: University of Arizona Press.

Simmons, A. H., Köhler-Rollefson, I., Rollefson, G. O., Mandel, R., and Kafafi, Z., 1988. 'Ain Ghazal: a major Neolithic settlement in central Jordan. *Science*, **240**(4848), 35–39.

Von den Driesch, A., and Wodtke, U., 1997. The fauna of 'Ain Ghazal, a major PPN and Early PN settlement in central Jordan. In Gebel, H. G., Kafafi, Z., and Rollefson, G. O. (eds.), *The Prehistory of Jordan. II. Perspectives from 1997*. Berlin: Ex Oriente. Studies in Early Near Eastern Production, Subsistence, and Environment, 4, pp. 511–556.

Zielhofer, C., Clare, L., Rollefson, G., Wächter, S., Hoffmeister, D., Bareth, G., Roettig, C., Bullmann, H., Schneider, B., Berke, H., and Weninger, B., 2012. The decline of the Early Neolithic population center of 'Ain Ghazal and corresponding earth-surface processes, Jordan Rift Valley. *Quaternary Research*, **78**(3), 427–441.

AKROTIRI *AETOKREMNOS*, CYPRUS

Rolfe D. Mandel[1] and Alan H. Simmons[2]
[1]Department of Anthropology, University of Kansas, Lawrence, KS, USA
[2]Department of Anthropology, University of Nevada Las Vegas, Las Vegas, NV, USA

Akrotiri *Aetokremnos* is a collapsed rock shelter on the southern coast of Cyprus's Akrotiri Peninsula. The site is on a steep cliff overlooking the Mediterranean Sea, some 40 m below. Excavations at *Aetokremnos*, in 1987–1988 and 1990, uncovered a 1.0–1.5 m thick package of deposits preserved beneath massive roof-fall blocks. These deposits contained cultural features and artifacts in direct association with huge amounts (nearly 300,000 bones representing at least 505 individual animals) of extinct pygmy hippopotamus (*Phanourios minutus*) and pygmy elephant (*Elephas cypriotes*) representing at least three individuals, as well as numerous bird and shell remains (Simmons, 1999).

Aetokremnos is the oldest well-documented archaeological site in Cyprus. Full details of its radiocarbon chronology are provided in Simmons and Wigand (1994). A total of 36 radiocarbon determinations are available for the site. Three of these were from surface specimens, and the remainder was from sealed contexts. Materials dated included marine shell, *Phanourios* bone, sediment, and charcoal. Based on statistical analyses, *Aetokremnos* was occupied for a relatively short time centered around 11,800 cal. BP. Even with newly documented Pre-Pottery Neolithic A (PPNA) sites on the island (Manning et al., 2010; Vigne et al., 2011), *Aetokremnos* predates the Neolithic occupation by about 500 years.

A total of 1,021 chipped stone artifacts were recovered from *Aetokremnos*. Over 95 % came from subsurface contexts, many in stratigraphic association with burned and unburned bones. Small, well-made "thumbnail" scrapers dominate the assemblage of 128 formal, retouched tools. Other tools include additional scraper forms, burins, retouched pieces, truncations, notches, and microliths. All of these artifacts were manufactured using locally available materials.

Geoarchaeological investigations of *Aetokremnos* were undertaken during the course of the excavation, in part to answer the questions raised concerning the association of the cultural materials and faunal remains (Mandel and Simmons, 1997). Four major stratigraphic units, numbered 1–4 from uppermost to lowermost, were identified at the site, with cultural features and artifacts concentrated in Strata 2 and 4. The duration of human occupation, as represented by cultural deposits in these two strata, was relatively short, perhaps a few hundred years or less.

Most of the sediments that accumulated in the rock shelter are a product of roof fall, disintegration of bedrock (attrition), and wind action. In addition, a small volume of slopewash entered the back of the shelter through solution cavities and is confined to less than 5 % of the site. Although some of the strata have been slightly affected by leaching and clay translocation, there is no evidence of soil development in the shelter. The physical and geochemical properties of the strata indicate that the sediments and associated cultural materials rapidly accumulated on the floor of the shelter soon before the roof collapsed, isolating the underlying deposits from subaerial weathering and other site-disturbance processes. This explains why there has been very little mixing of artifacts and bones between Strata 2 and 4; the cultural deposits at *Aetokremnos* have near-pristine vertical and horizontal integrity.

In summary, *Aetokremnos* is significant for two reasons. First, it is among the best-documented ancient sites on any of the Mediterranean islands. Second, and more controversially, artifacts are associated with the extinct endemic island fauna, notably pygmy hippopotami. Prior to the discoveries at *Aetokremnos*, such an association had never before been demonstrated, and humans may have been partially responsible for the early Holocene extinction of these unique animals (Simmons and Mandel, 2007).

Bibliography

Mandel, R. D., and Simmons, A. H., 1997. Geoarchaeology of the Akrotiri *Aetokremnos* rockshelter, Cyprus. *Geoarchaeology*, **12**(6), 567–605.

Manning, S. W., McCartney, C., Kromer, B., and Stewart, S. T., 2010. The earlier neolithic in Cyprus: recognition and dating of a pre-pottery neolithic a occupation. *Antiquity*, **84**(325), 693–706.

Simmons, A. H., 1999. *Faunal Extinction in an Island Society: Pygmy Hippopotamus Hunters of Cyprus*. New York: Kluwer/Plenum.

Simmons, A. H., and Mandel, R. D., 2007. Not such a new light: a response to Ammerman and Noller. *World Archaeology*, **39**(4), 475–482.

Simmons, A. H., and Wigand, P. E., 1994. Assessing the radiocarbon determinations from Akrotiri *Aetokremnos*, Cyprus. In Bar-Yosef, O., and Kra, R. S. (eds.), *Late Quaternary*

Chronology and Paleoclimates of the Eastern Mediterranean. Radiocarbon/Cambridge, MA: Tucson/American School of Prehistoric Research, Harvard University, pp. 247–254.

Vigne, J.-D., Briois, F., Zazzo, A., Carrère, I., Daujat, J., and Guilaine, J., 2011. A new early pre-pottery neolithic site in Cyprus: Ayios Tychonas-*Klimonas* (ca. 8700 cal. BC). *Neo-Lithics*, **1**(11), 3–18.

ALLUVIAL SETTINGS

C. Reid Ferring
Department of Geography, University of North Texas, Denton, TX, USA

Definition

The term alluvial geoarchaeology denotes the practice of geoarchaeology in fluvial drainage systems, with an emphasis on the discovery, excavation, and contextual analysis of archaeological records in alluvium, i.e., sediments deposited by water, and existing within varied alluvial settings.

Introduction

The study of alluvial systems and their geologic records has been an important part of the earth sciences since the 1830s, when Charles Lyell focused on alluvial records as part of his famous *Principles of Geology*. In his *Antiquity of Man* (1869), arguably the first major work in geoarchaeology, Lyell recounted many discoveries of artifacts and fossils in alluvium, using these to present one of the first chronicles of human cultural and environmental history.

Since that publication, archaeologists and geologists have constructed an increasingly detailed record of human occupations in alluvial environments. The oldest known stone artifacts, 2.6 million-year-old flakes and cores, were recovered from alluvial sediments of the paleo-Awash River in Gona, Ethiopia (Semaw et al., 2003). Succeeding phases of cultural evolution are documented by Paleolithic finds in Africa and Eurasia that were preserved in alluvial deposits (van Andel and Tzedakis, 1996; Potts et al., 1999; Holliday et al., 2007; Rosen, 2008; Patnaik et al., 2009; Marder et al., 2011), and some of the most important sites bearing on the peopling of the New World are preserved in alluvium (Wagner and McAvoy, 2004; Haynes and Huckell, 2007; Mandel, 2008; Waters et al., 2011). In both the Old World and the New World, intense utilization of fluvial environments by sedentary agriculturalists has also been documented by geoarchaeologists (Rosen, 1997; Guccione, 2008; Huckleberry and Duff, 2008; Nials et al., 2011).

Today, it is both important and challenging to summarize this branch of geoarchaeology because so much highly productive archaeological research is conducted in alluvial settings. Accordingly, alluvial settings figure prominently in major works on geoarchaeology (Butzer, 1982; Needham and Macklin, 1992; Waters, 1992; Brown, 1997; Rapp and Hill, 1998; Holliday, 2004). There are three main reasons for this. First, humans have always exploited alluvial environments because they provide water, diverse food resources, fuel, and means of travel and transport. Second, alluvial sedimentation promotes burial and preservation of archaeological sites. Third, alluvial landforms, sediments, soils, and associated paleontological materials provide excellent opportunities to place archaeological records in temporal and environmental context. Significant overlap in the goals, strategies, and methods of alluvial geoarchaeology exists with geoarchaeological investigations conducted in other geologic settings, and therefore, consulting the cross-referenced entries in this encyclopedia will provide expanded discussions and illustrations of many issues considered here.

The goal of the following discussions is to provide an overview and guide to further study of both alluvial geology and how geoarchaeology is practiced in alluvial settings. This is supported by references to general works and specific investigations that illustrate major features of alluvial systems and many aspects and results of geoarchaeological research.

Alluvial geology and geomorphology

Students of alluvial geoarchaeology can benefit from the extensive treatment of alluvial geology in both introductory and advanced texts. Streams and rivers are introduced in all textbooks on physical geology. Geomorphology texts, such as Bloom (2004) or Ritter et al. (2011), provide thorough reviews of alluvial processes and the resulting geologic records of landforms and bodies of sediment. Other recommended sources on alluvial geology include Schumm (1977) and Leopold (1994). A major focus of many syntheses is the responses by streams to climate change; these responses prove to be especially pertinent to the interests of archaeologists, who seek to document and understand ancient cultural responses to climatic and environmental changes over long intervals (Knox, 1983; Bull, 1991; Frederick, 2001; Macklin and Lewin, 2008). The following discussions will illustrate that geoarchaeologists also contribute directly to alluvial geology in the course of their research. First, an overview of alluvial geology is presented by way of an introduction to the major kinds of processes that have shaped alluvial geologic records; then the discussions turn to major issues in the field of alluvial geoarchaeology.

On the most general level, alluvial geology is the study of landforms, sedimentary deposits, and associated features that are the result of erosion, transport, and deposition within a drainage system. Drainage systems comprise a trunk stream and its tributaries, and they are defined by topographic catchments whose boundaries are in turn delineated by interfluves (essentially, ridges that divert surface runoff of precipitation into one or another drainage). The drainage basin for a given system extends from its headwaters to its termination in an ocean or lake basin. Streams and their tributaries exhibit marked changes in behavior and scale along a downstream (longitudinal) direction. Such changes in typical drainages include: (a) a decrease in channel gradient (steepness), (b) an increase in discharge (the volume of water per unit of time passing a point along the channel), (c) an increase in the sinuosity of the channel, (d) an increase in the load of the stream (the solid and dissolved materials carried in the water), and (e) an increase in sediment storage (alluvial deposits). Over time, a typical stream and its tributaries will erode down through the bedrock creating an increasingly large system of valleys that are connected at confluences. Stream valleys typically preserve sediment (alluvium) that was deposited in channels and on floodplains (the portion of the valley that is periodically inundated by floodwaters). Because archaeological sites are often buried in alluvium, deposits under floodplains and terraces are the target of archaeological surveys and subsequent excavations, as discussed below.

Most alluvial systems are subject to periodic and/or episodic changes in geologic activity. Floods are the most common kinds of change. The frequency and magnitude of floods vary considerably. In general, the common, smaller floods result in (a) the addition of sediment to floodplains (alluviation) when high water overflows a stream's banks and (b) minor shifts in channel positions. Over periods of centuries or even millennia, these changes often appear to have been quite gradual. However, large floods, as well as external forces such as climate change or tectonic activity, can effect more significant changes, including entrenchment of the channel into the underlying bedrock or older alluvium. Such incision can be accompanied by *floodplain abandonment*, which transforms the former floodplain into a terrace (a bench-like landform that stands above the new, active floodplain). Multiple terraces signify several episodes of valley entrenchment, with increasingly older sediments preserved under each higher terrace surface (Bull, 1990; Bridgland and Westaway, 2008).

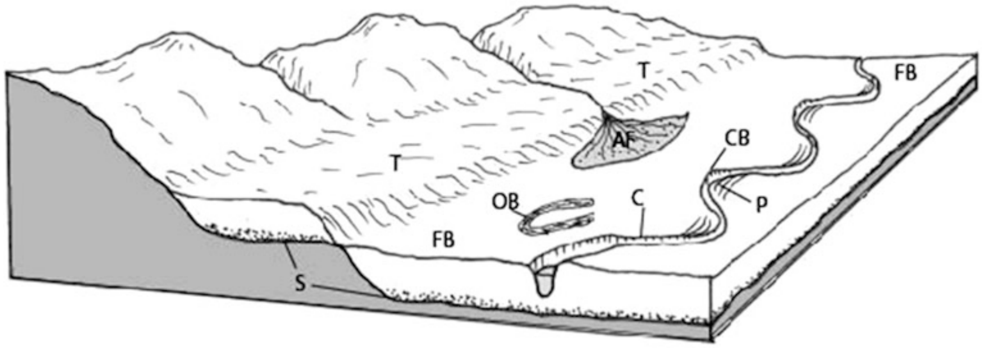
Sedimentation on floodplains

The accumulation (aggradation) of sediments on the floodplains of streams and rivers is usually the most important aspect of alluvial geology for archaeologists simply because this is the means by which archaeological sites are buried and preserved (Ferring, 1986a; Ferring, 2001). Floodplain sediments register the response of the fluvial system to both internal and external agents, and therefore, they are a major focus for geologists who study alluvial records with regard to climate change, tectonics, sea-level fluctuations, and other factors. The most important differences in alluvial geology are caused by climatic and tectonic factors (Frederick, 2001). In terms of climate, it is important to contrast alluvial processes and geologic records that occur within humid environments (Ferring, 1990; Mandel, 1995; Ferring, 2001; Bettis et al., 2008; Guccione, 2008; Kesel, 2008) to those that occur within arid ones (Cooke and Warren, 1973; Patton and Schumm, 1981; Freeman, 2000; Waters, 2000; Cordova et al., 2005; Butzer et al., 2008; Harden et al., 2010). Tectonic controls on alluvial geology are frequently important, especially in ancient contexts (Bull, 1991; Noller, 2001), e.g., many of the important Lower Pleistocene archaeological records from East African Rift valleys come from alluvial settings that were subject to tectonic processes (Potts et al., 1999; Feibel, 2004; Sikes and Ashley, 2007; Feibel, 2008; Domínguez-Rodrigo et al., 2009; Feibel et al., 2009). Within these different settings, the varied contexts condition the general processes of alluviation, soil formation, and erosion on floodplains.

It is convenient to consider floodplain sedimentation in two major settings: in and near channels and farther from channels within the flood basin (Lewin, 1978). Different kinds and rates of deposition on a floodplain result in the construction of distinctive landforms called depositional geomorphic features; these include point bars, cutbanks, natural levees, and the flood basin (Figure 1). In addition to these geomorphic features, the properties and contents of the sediments (called sedimentary facies) are used to reconstruct the particular depositional setting, more properly called the sedimentary environment.

Alluvial sedimentary *facies* are "packages" of sediment in the geologic record that are defined by their texture (grain size), sedimentary structures (such as bedding), and their organic content (Miall, 1992). Facies analysis includes the description and study of those properties in order to identify and reconstruct the sedimentary environments responsible for their creation in space and time. The analysis is conducted together with actualistic comparisons to modern streams so that characteristics of the older sediments can be compared to those typical of ongoing depositional processes. This is especially important in the study of geoarchaeological records, because both past occupation potentials and site formation processes vary considerably by specific depositional environment. Based on extensive studies, many alluvial facies have been formally defined by sedimentologists (Reineck and Singh, 1980; Miall, 1992; Houben, 2007).

An exposure of sediments in a cutbank of the Trinity River in Texas illustrates a sequence of alluvial facies (Figure 2). The lower part of the section consists of steeply dipping beds of sand and silt that "fine upwards," i.e., become finer higher in the section; these were deposited on a point bar. As the channel migrated away from this location, the environment shifted to that of a flood basin, where episodic deposition of clays was accompanied by soil formation from ca. 2000 to 1000 BP (Ferring, 1990; Ferring, 1992). Later, the channel returned to this position, and the natural levee deposits (thin beds of sand and silt) accumulated. This is a common sequence of facies, which are stacked into a vertical "facies association" (Miall, 1992). Note that this sequence of sediments records a spatial shift in sedimentary environment because



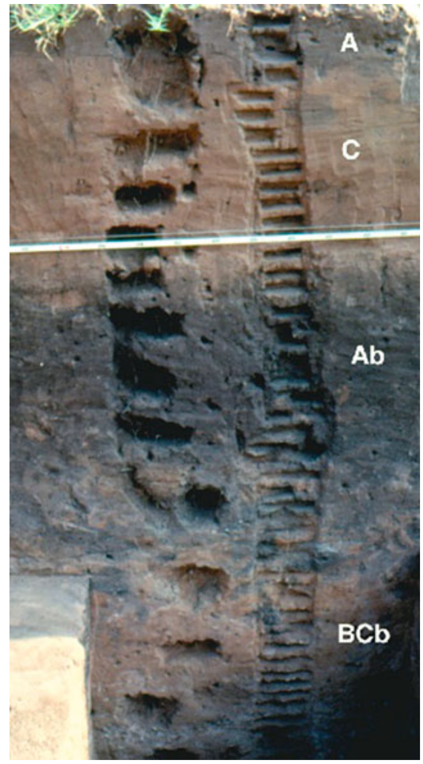
Alluvial Settings, Figure 1 Geologic features of a meandering river valley. Note the major sedimentary environments: *C* channel, *P* point bar, *CB* cutbank, *FB* flood basin, *OB* oxbow lake, *T* terrace, *S* strath, *AF* alluvial fan. Point bars are locations on the inside, or convex, banks of a meandering stream where sediment tends to be deposited. Cutbanks are steep erosional surfaces on the opposite outside, or concave, banks of a meandering stream. Oxbow lakes are rounded bodies of water created when extreme meander bends in the river join and give rise to a straighter main stream and a curved cutoff filled with standing water. Straths are terraces previously etched into underlying bedrock prior to alluvial buildup within a valley.

Alluvial Settings, Figure 2 Sedimentary facies of alluvium on the West Fork Trinity River in northern Texas. This cutbank exposes sediments of a Late Holocene point bar and floodplain, overlain by a recent natural levee.

meandering channels constantly migrate laterally across the floodplain. These normal variations in floodplain alluviation need to be documented prior to making unsubstantiated assertions, for example, suggesting that they reflect a change in climate. As discussed below, the prospects for finding preserved archaeological materials in a section like this are best in the floodplain clays, which accumulated for a longer period of time in a setting favored by Archaic and late prehistoric populations, ca. 3000–600 BP. The levee deposits accumulated after the arrival of Europeans.

Alluvial facies vary significantly in both space and time. Meander belts are the zone within valley floors across which meandering rivers periodically shift their courses; rapid sediment buildup along these meander belts can promote avulsion of the channel system to a lower part of the floodplain (Ferring, 1992; Törnqvist and Bridge, 2002; Phillips, 2011). Longitudinal (downstream) changes in facies are also common, owing to increases in discharge, changes in sediment load, and changes in bedrock geomorphic controls such as valley constrictions. Because of higher gradients, greater erosional potentials, and different vegetation patterns, alluviation in tributary streams can leave records that differ significantly from those in trunk streams. This is well documented in valleys of the Great Plains, which contain rich archaeological records (Mandel, 1995; Bettis and Mandel, 2002; Bettis et al., 2008; Mandel, 2008).

The rate of sedimentation is a significant variable in the record of alluvial sediments and associated archaeological materials (Ferring, 1986a). Indeed, the rate of sedimentation largely defines the potential for preservation of alluvium (Lewin and Macklin, 2003), as well as archaeological materials deposited on floodplains. Even without changes in climate or other external factors, sedimentation rates vary across floodplains, mainly in response to more rapid deposition of coarser (sand and silt) sediments near channels. When flooding rivers overrun their banks, the swift moving water slows down as it escapes the confines of its channel, and coarser sediments entrained by the formerly rapid flow are dropped closer the channel. This deposition results in the construction of raised meander belts, as mentioned above. Slower deposition in distal floodplain settings (i.e., farther from channels) is usually associated with finer suspended sediments (clay and silt) that are carried a greater distance away by floodwaters. Rates of sedimentation are also controlled by geomorphic factors, such as valley constrictions that impound floodwaters. Significantly, overall rates of floodplain aggradation may "wane" in response to long-term aggradation, which effectively raises floodplains above their channel bases. However, one of the most important implications of changing rates of sedimentation concerns soil formation on floodplains (Ferring, 1992).



Alluvial Settings, Figure 3 Profile at Delaware Canyon, Oklahoma, with an overthickened, buried soil (Ab). This soil preserved stratified Plains Woodland artifacts, faunas, and features. The small sample holes were for pollen analysis, while the larger samples were used for physical and chemical analyses of the sediments and soils. The lack of visible stratigraphy within the soil horizons mandated the use of arbitrary 5 cm levels for excavation.

Alluvial soils

The study of alluvial soils is important for both geologic and archaeological investigations. Alluvial soils, like those that form in other environments, are indicators of surface stability (Holliday, 1992; Birkeland, 1999; Holliday, 2004). On floodplains, soil formation signifies reduced rates of deposition, which allows time for soil profiles to develop. While some alluvial soils simply register a shift in sedimentary environments as mentioned above, regional climatic changes resulting in penecontemporaneous soil formation in multiple drainages are well documented (Ferring, 1990; Ferring, 1992; Mandel and Bettis, 2001; Beeton and Mandel, 2011). Particularly in North American settings, where archaeological records are dominantly Holocene in age, floodplain soils are generally weakly developed. Soils with A-C profiles are the most common, although weakly developed B horizons (Bw, Bk, or Bt) are found in some settings (Holliday, 2004).

Especially for geoarchaeological investigations, it is important to consider that floodplain alluviation and soil development often occurred simultaneously. In these cases, soil development alters the original properties of the sediment. This situation led to the definition of "pedofacies" (Kraus and Brown, 1988) or "soil facies" (Holliday, 2004, 79), which recognizes variations in alluvial sediments caused by the formation of soil features. This is particularly common in soils formed on floodplains. One consequence of time-transgressive deposition and soil development is the formation of *cumulic soils* (Birkeland, 1999, 165; Holliday, 2004, 90). A common result of cumulization is the development of overthickened soils, particularly thick A horizons. An example developed in Late Holocene alluvium at Delaware Canyon, Oklahoma, is shown in Figure 3. The overthickened buried A horizon (Ab) formed roughly between 1900 and 1000 BP, and it contains well-preserved artifacts and faunas of Plains Woodland groups who repeatedly camped on the floodplain of Delaware Creek (Ferring, 1986b). In the photo, note that the Ab horizon is underlain by a weakly developed B horizon. Prominent krotovina (rodent burrows), with several generations of fill, testify to post-occupational disturbance. The fill from these burrows was excavated separately and discarded to minimize the effects of mixture of bone and artifacts between occupation surfaces. Analysis of alluvial soils is a key component of site formation studies, as discussed below.

Site discovery

Methods for archaeological survey in floodplain settings must be tailored to the fact that many sites are deeply buried. Perhaps the most common means for discovering deeply buried sites is by careful examination of natural cutbank exposures (Figure 3). During such surveys, particular attention is paid to sedimentary facies and buried soils, which are important guides to both the age and depositional environments pertinent to site discovery. Well-established stratigraphic-soil sequences have been developed to target particular temporal/cultural periods. On the Great Plains, survey strategies have been developed for the whole range of cultural periods, including Paleoindian (Bettis et al., 2008; Mandel, 2008), Archaic (Mandel, 1995), and Late Prehistoric (Ferring, 1990). It should be noted that surface surveys of large, complex river systems are also an important research strategy (Wells, 2001). An exemplary case study is the survey of sites in the Missouri, Red, and Mississippi River valleys by Guccione (2008). Hundreds of sites were located in diverse geologic settings, resulting in a comprehensive analysis of settlement intensity and settlement patterns over the Holocene.

Both mechanical techniques and remote sensing are also useful in the survey of alluvial deposits. Coring and trenching are frequently used to discover buried sites under floodplains. Both methods were used in the Ohio River Valley to define geologic contexts as well as discover deeply buried Woodland and Late Prehistoric age sites (Stafford and Creasman, 2002). Similar approaches were used to explore alluvial deposits that buried a series of Middle Holocene (ca. 5000 BP) Archaic mounds in the lower Mississippi Valley (Arco et al., 2006). Rosen (1997) used trenching as well as natural exposures to locate and study Neolithic-Bronze Age sites in Turkey. Remote sensing techniques include resistivity, magnetometry, and ground-penetrating radar (Kvamme, 2001). These approaches are best geared to defining the lithology and contacts of buried alluvial units, as a prelude to mechanical testing.

Alluvial terraces

Alluvial terraces are landforms created by the abandonment of a floodplain by means of channel incision or entrenchment (Bull, 1990). This process may be caused by tectonic uplift, climate change, or, in localities near coasts, falling sea level (Bull, 1991). When alluvial deposition slows or ceases, permitting a transition to surface stability, the sediments below the terrace surface are subjected to new soil-forming environments. Soils on progressively higher, older terraces (Figure 4) have developed over longer periods, resulting in a soil chronosequence running up through the terrace structure (Birkeland, 1999, 192). Because of the relatively recent peopling of the New World, sites buried in terrace deposits are uncommon in North and South America; however, the surfaces of terraces were favored locations for Late Pleistocene and Holocene occupations because of their proximity to streams coupled with protection from floods (Ferring, 1992; Guccione, 2008). Archaeological records within terrace deposits are quite common in the Old World because of the much greater time depth of occupations compared to the New World (van Andel and Tzedakis, 1996; Cordova et al., 2005; Schuldenrein, 2007; Patnaik et al., 2009).

Alluvial fans and colluvium

Sediments derived from steep valley slopes are frequently deposited along the margins of valleys, where they can accumulate on terrace surfaces or become interstratified with floodplain deposits. These deposits include generalized slope deposits called *colluvium* and more discrete bodies called *alluvial fans*, described below. Because these deposits represent aggrading surfaces usually above the active floodplain, they were frequently occupied and are generally good environments for the preservation of archaeological sites. Colluvium is most often preserved as "aprons" along the base of slopes, underlain by sediments that accumulated as a result of gravity (creep or mass movements) and/or sheet wash (Bloom, 2004). Changes in sediment supply, precipitation, and vegetative cover are among the factors that led to alternating periods of rapid deposition and periods of slower deposition with soil formation along valleys of the Midwestern United States (Bettis, 2003). Numerous archaeological sites are preserved in those colluvial deposits. At the famous Paleolithic Kostenki-Borschevo sites in Russia, colluvial deposits are interstratified with alluvium, loess, and volcanic ashes (Holliday et al., 2007). In China, a Middle-Upper Pleistocene series of terraces, each with associated alluvial fans, has been defined and dated as part of an intensive survey for Paleolithic sites (Lu et al., 2010).

Alluvial fans comprise major sedimentary environments that have been studied in many settings, ranging from humid to arid (Reineck and Singh, 1980, 298; Miall, 1992). In contrast to colluvium, alluvial fans are distinct, fan-shaped depositional landforms that develop at the intersection of steep tributaries with either terrace surfaces or floodplains. In desert settings, adjacent alluvial fans often coalesce into continuous features called *bajadas* (Bloom, 2004). Alluvial fans are characterized by intermittent sedimentation, with frequent shifting of channel/gully positions, and a general fining of sediment texture from proximal to distal positions down the fan to the bottom, where closed playa lakes are common. Especially in

Alluvial Settings, Figure 4 Alluvial terraces and soils: (**a**) Late Pleistocene terrace of the Tedzami River near Gori, Republic of Georgia; (**b**) Late Pleistocene terrace deposits and soil on the Trinity River near Dallas, Texas. The soil of the Trinity River deposits has been forming since the Late Pleistocene floodplain was abandoned by incision ca. 22–25 Ka. Surficial archaeological sites, often palimpsests created by the superposition of repeated occupations, are common on the terrace surface, while fossils of extinct fauna are preserved in the underlying sediments of the sandy channel facies.

humid environments, such as in the Midwestern United States, alluvial fans have built up over earlier Holocene deposits, preserving numerous archaeological sites underneath (Bettis and Mandel, 2002; Bettis, 2003). Periods of slower fan aggradation were accompanied by soil formation, which assist in stratigraphic correlation among different fans. Alluvial fans were commonly chosen for occupation from the Early to the Late Holocene, as illustrated by excavations at the Koster and Napoleon Hollow sites in the Illinois River Valley (Wiant et al., 1983.) Alluvial fans and bajadas are very common in the western deserts of the United States, and they are prime targets for archaeological surveys (Waters, 1992, 2000; Nials et al., 2011).

Eolian deposits

Eolian sands or loess are frequently found in association with fluvial deposits, especially in the Midwestern United States. Pleistocene loess is a major source for younger alluvium that now fills river valleys (Mandel, 1995; Mandel and Bettis, 2001; Bettis and Mandel, 2002; Bettis et al., 2008). Eolian sands accumulated along drainages in the southwestern United States and buried early Holocene sediments in the “draws” of the Southern High Plains (Holliday, 1995). At the Mockingbird Gap site in New Mexico, Clovis artifacts were buried in eolian sands along Chupadera Draw (Holliday et al., 2009). Research in those settings illustrates the careful geologic analysis of sediments and soils necessary to reconstruct sedimentary environments and site formation processes, both of which are important goals of most geoarchaeological studies.

Paleoenvironmental studies

Alluvial deposits often preserve important evidence of past environments, which is frequently studied in concert with archaeological investigations. As described above, alluvial facies provide records of sedimentary change, especially in response to environmental shifts (Knox, 1983; Bull, 1991; Bettis et al., 2009; van de Wiel et al., 2011), and alluvial soils are also used extensively as part of paleoenvironmental studies (Holliday, 2004). Study of stable isotopes of carbon and oxygen is conducted on both organic matter and pedogenic carbonates in alluvial soils (Humphrey and Ferring, 1994; Nordt, 2001; Sikes and Ashley, 2007). Changes in patterns of sedimentation as well as soil formation on floodplains need to be investigated first with respect to normal shifts in sedimentary environments (Figure 3), however.

Site formation processes

Site formation studies are important in virtually all geoarchaeological contexts (Butzer, 1982). In alluvial settings, formation processes and formation histories are complex, owing to different rates and patterns of sedimentation and exposure on floodplains and terraces (Ferring, 1992; Ferring, 2001). In the main, floodplains are good formation contexts because burial occurs by low-energy, post-occupational deposition. However, rates of sedimentation vary markedly both longitudinally (downstream) and in different sedimentary environments within shorter reaches of a valley (Ferring, 1986a). Rates of sedimentation are important to document, for they exert strong controls on formation processes during and after occupations, often resulting in marked differences in artifact density and bone preservation among sites.

Sites in alluvial settings are subject to many weathering and disturbance processes, including bioturbation and pedoturbation (Wood and Johnson, 1978), which highlights the need for careful analysis of both sediments and soils, as at the Cactus Hill site (Wagner and McAvoy, 2004) and the Big Eddy site in Missouri (Hajic et al., 2007), both of which contain important records of Paleoindian occupations. There are often strong textural controls on formation processes. Sites that formed in sandy alluvium may be more prone to artifact trampling and bioturbation by insects and micromammals (see Figure 3). Fine-grained (clay-silt) sediments, common to floodplains, are more prone to pedoturbation by shrink-swell of vertisols and turbation by earthworms. Field observations and standard textural-chemical lab analyses are often supported by micromorphology, providing detailed evidence about sedimentary environments, soils, and anthropogenic features (Courty, 2001; Macphail and Cruise, 2001; Domínguez-Rodrigo et al., 2009). At the Friedkin site in Texas, micromorphology was applied to study possible effects of pedoturbation within Paleoindian and "pre-Clovis" deposits (Waters et al., 2011).

Stratigraphy and dating

Alluvial records often provide excellent opportunities for establishing detailed chronologies for sediments and their entrained archaeological and paleoenvironmental data (van Andel and Tzedakis, 1996; Frederick, 2001; Macklin et al., 2002; Holliday, 2004; Feibel, 2008). As in other settings, most efforts at dating begin with stratigraphic studies of landforms, sediments, and soils. Morphostratigraphy addresses the sequence of alluvial landforms – including terraces – and alluvial fans, as well as depositional landforms such as floodplains, natural levees, cutoff channels, and oxbow lakes (Wells, 2001). The stratigraphic relations of these landforms are usually established by field description and mapping; however, the use of remote sensing (such as air photos and satellite images) is an increasingly productive approach (Guccione, 2008). In many cases, buried soils are critical stratigraphic markers, both within and between drainages (Holliday, 1995; Holliday, 2004). Allostratigraphic units are formally defined stratigraphic units in alluvial contexts (Miall, 1992; NACSN, 2004). These are packages of alluvial sediments, often comprising different facies, which are defined on the basis of bounding discontinuities, such as soils (representing intervals of stability) or erosional disconformities (representing intervals of sediment loss and the creation of abrupt discontinuities within the stratigraphic sequence). Although these are lithostratigraphic units – defined on the basis of sedimentary units in contact with one another – they also provide the necessary framework to support sampling for chronometric dating, leading to the definition of chronostratigraphic units.

Absolute dating of alluvial deposits employs a range of specific methods that are chosen to meet the availability of datable materials as well as the age range of the deposits. Radiocarbon dating is the most commonly employed method for deposits less than about 40,000 years old; however, optically stimulated luminescence (OSL) is increasingly used on silicate fractions of sediments, despite the generally high error factors (Holliday et al., 2007; Waters et al., 2011). For older deposits, uranium-thorium dating of pedogenic carbonates (Sharp et al., 2003) and Ar/Ar dating of associated volcanic rocks and sediments are employed (Feibel et al., 2009; Zaim et al., 2011).

In the central and eastern Great Plains, comprehensive stratigraphic sequences (lithosequences and chronosequences) of Late Quaternary alluvial deposits have been established, resulting in a framework for the discovery and study of archaeological records (Bettis and Mandel, 2002). A detailed stratigraphic framework has been developed for locating Paleoindian sites in the central Great Plains by Mandel (2008); a stratigraphic basis for site discovery was also developed for the Cottonwood River Basin in Kansas (Beeton and Mandel, 2011). Other useful examples of alluvial stratigraphy include the work in the lower Mississippi Valley (Kesel, 2008), the upper Mississippi Valley (Bettis et al., 2008), and in Holocene deposits in France (Berger, 2011). In the southwestern deserts of the United States, complex alluvial stratigraphic records have been established on the basis of both lithostratigraphy and radiocarbon dating (Waters, 2000). An excellent example is the work done in the San Pedro Valley (Arizona), where Haynes (2007) conducted detailed stratigraphic-dating research at the famous Murray Springs site (Haynes and Huckell, 2007). There, a superb record of Clovis activities was recovered at the base of a thick alluvial sequence (Figure 5).

Summary

This brief summary of alluvial geoarchaeology has demonstrated that many important records of human history are preserved in sediments and on landforms created by streams. Although much geoarchaeological research is conducted in other geologic settings, many archaeologists and the geologists/geomorphologists they collaborate with will work in alluvial settings at some time in their career. For them, much can be learned from the older, important works, as well as the many recent examples of research cited here. This is especially true for archaeologists engaged in Cultural Resource Management (CRM), since many land use projects impact archaeological records in alluvial settings. Both CRM investigations

Alluvial Settings, Figure 5 Alluvial deposits along Curry Draw, Arizona. Note the vertical walls of the modern arroyo, typical of desert streams. Clovis artifacts and fossils of numerous extinct megafauna were found just below the prominent "black mat" in the lower part of the section. These have been dated to ca. 10940 BP (Haynes, 2007).

and grant-supported research should exploit the contributions of alluvial geologists and geoarchaeologists as they design and implement research strategies. The extensive body of published research on alluvial geoarchaeology, some of which is cited here, is an important resource for researchers developing programs of site discovery, excavation, and contextual study.

Bibliography

Arco, L. J., Adelsberger, K. A., Hung, L.-Y., and Kidder, T. R., 2006. Alluvial geoarchaeology of a Middle Archaic mound complex in the lower Mississippi Valley, U.S.A. *Geoarchaeology*, **21**(6), 591–614.

Beeton, J. M., and Mandel, R. D., 2011. Soils and late-Quaternary landscape evolution in the Cottonwood River basin, east-central Kansas: implications for archaeological research. *Geoarchaeology*, **26**(5), 693–723.

Berger, J.-F., 2011. Hydrological and post-depositional impacts on the distribution of Holocene archaeological sites: the case of the Holocene middle Rhône River basin, France. *Geomorphology*, **129**(3–4), 167–182.

Bettis, E. A., III, 2003. Patterns in Holocene colluvium and alluvial fans across the prairie-forest transition in the midcontinent USA. *Geoarchaeology*, **18**(7), 779–797.

Bettis, E. A., III, and Mandel, R. D., 2002. The effects of temporal and spatial patterns of Holocene erosion and alluviation on the archaeological record of the Central and Eastern Great Plains, U.S.A. *Geoarchaeology*, **17**(2), 141–154.

Bettis, E. A., III, Benn, D. W., and Hajic, E. R., 2008. Landscape evolution, alluvial architecture, environmental history, and the archaeological record of the Upper Mississippi Valley. *Geomorphology*, **101**(1–2), 362–377.

Bettis, E. A., III, Milius, A. K., Carpenter, S. J., Larick, R., Zaim, Y., Rizal, Y., Ciochon, R. L., Tassier-Surine, S. A., Murray, D., Suminto, and Bronto, S., 2009. Way out of Africa: early Pleistocene paleoenvironments inhabited by *Homo erectus* in Sangiran, Java. *Journal of Human Evolution*, **56**(1), 11–24.

Birkeland, P. W., 1999. *Soils and Geomorphology*, 3rd edn. New York: Oxford University Press.

Bloom, A. L., 2004. *Geomorphology: A Systematic Analysis of Late Cenozoic Landforms*, 3rd edn. Long Grove: Waveland.

Bridgland, D., and Westaway, R., 2008. Climatically controlled river staircases: a worldwide Quaternary phenomenon. *Geomorphology*, **98**(3–4), 285–315.

Brown, A. G., 1997. *Alluvial Geoarchaeology: Floodplain Archaeology and Environmental Change*. Cambridge: Cambridge University Press.

Bull, W. B., 1990. Stream-terrace genesis: implications for soil development. *Geomorphology*, **3**(3–4), 351–367.

Bull, W. B., 1991. *Geomorphic Responses to Climate Change*. New York: Oxford University Press.

Butzer, K. W., 1982. *Archaeology as Human Ecology: Method and Theory for a Contextual Approach*. Cambridge: Cambridge University Press.

Butzer, K. W., Abbott, J. T., Frederick, C. D., Lehman, P. H., Cordova, C. E., and Oswald, J. F., 2008. Soil-geomorphology and "wet" cycles in the Holocene record of north-central Mexico. *Geomorphology*, **101**(1–2), 237–277.

Cooke, R. U., and Warren, A., 1973. *Geomorphology in Deserts*. Berkeley: University of California Press.

Cordova, C. E., Foley, C., Nowell, A., and Bisson, M., 2005. Landforms, sediments, soil development, and prehistoric site settings on the Madaba-Dhiban Plateau, Jordan. *Geoarchaeology*, **20**(1), 29–56.

Courty, M.-A., 2001. Microfacies analysis assisting archaeological stratigraphy. In Goldberg, P., Holliday, V. T., and Ferring, C. R. (eds.), *Earth Sciences and Archaeology*. New York: Kluwer Academic/Plenum, pp. 205–239.

Domínguez-Rodrigo, M., Mabulla, A., Bunn, H. T., Barba, R., Diez-Martín, F., Egeland, C. P., Espílez, E., Egeland, A., Yravedra, J., and Sánchez, P., 2009. Unraveling hominin behavior at another anthropogenic site from Olduvai Gorge (Tanzania): new archaeological and taphonomic research at

BK, Upper Bed II. *Journal of Human Evolution*, **57**(3), 260–283.

Feibel, C. S., 2004. Quaternary lake margins of the Levant Rift Valley. In Goren-Inbar, N., and Speth, J. D. (eds.), *Human Paleoecology in the Levantine Corridor*. Oxford: Oxbow Books, pp. 21–36.

Feibel, C. S., 2008. Microstratigraphy of the Kibish hominin sites KHS and PHS, lower Omo Valley, Ethiopia. *Journal of Human Evolution*, **55**(3), 404–408.

Feibel, C. S., Lepre, C. J., and Quinn, R. L., 2009. Stratigraphy, correlation, and age estimates for fossils from Area 123, Koobi Fora. *Journal of Human Evolution*, **57**(2), 112–122.

Ferring, C. R., 1986a. Rates of fluvial sedimentation: implications for archaeological variability. *Geoarchaeology*, **1**(3), 259–274.

Ferring, C. R., 1986b. Late Holocene cultural ecology in the Southern Plains: perspectives from Delaware Canyon, Oklahoma. Memoir 21: current Trends in Southern Plains Archaeology, Part 2. *Plains Anthropologist*, **31**(114), 55–82.

Ferring, C. R., 1990. Archaeological geology of the Southern Plains. In Lasca, N. P., and Donahue, J. (eds.), *Archaeological Geology of North America*. Boulder: Geological Society of America. GSA Centennial Special, Vol. 4, pp. 253–266.

Ferring, C. R., 1992. Alluvial pedology and geoarchaeological research. In Holliday, V. T. (ed.), *Soils in Archaeology: Landscape Evolution and Human Occupation*. Washington, DC: Smithsonian Institution Press, pp. 1–39.

Ferring, C. R., 2001. Geoarchaeology in alluvial landscapes. In Goldberg, P., Holliday, V. T., and Ferring, C. R. (eds.), *Earth Sciences and Archaeology*. New York: Kluwer Academic/Plenum, pp. 77–106.

Frederick, C., 2001. Evaluating causality of landscape change: examples from alluviation. In Goldberg, P., Holliday, V. T., and Ferring, C. R. (eds.), *Earth Sciences and Archaeology*. New York: Kluwer Academic/Plenum, pp. 55–76.

Freeman, A. K. L., 2000. Application of high-resolution alluvial stratigraphy in assessing the hunter-gatherer/agricultural transition in the Santa Cruz River Valley, Southeastern Arizona. *Geoarchaeology*, **15**(6), 559–589.

Guccione, M. J., 2008. Impact of the alluvial style on the geoarchaeology of stream valleys. *Geomorphology*, **101**(1–2), 378–401.

Hajic, E. R., Mandel, R. D., Ray, J. H., and Lopinot, N. H., 2007. Geoarchaeology of stratified paleoindian deposits at the Big Eddy Site, southwest Missouri, U.S.A. *Geoarchaeology*, **22**(8), 891–934.

Harden, T., Macklin, M. G., and Baker, V. R., 2010. Holocene flood histories in south-western USA. *Earth Surface Processes and Landforms*, **35**(6), 707–716.

Haynes, C. V., Jr., 2007. Quaternary geology of the Murray Springs Clovis site. In Haynes, C. V., Jr., and Huckell, B. B. (eds.), *Murray Springs: A Clovis Site with Multiple Activity Areas in the San Pedro Valley, Arizona*. Tucson: University of Arizona Press, pp. 16–56.

Haynes, C. V., Jr., and Huckell, B. B. (eds.), 2007. *Murray Springs: A Clovis Site with Multiple Activity Areas in the San Pedro Valley, Arizona*. Tucson: University of Arizona Press.

Holliday, V. T. (ed.), 1992. *Soils in Archaeology: Landscape Evolution and Human Occupation*. Washington, DC: Smithsonian Institution Press.

Holliday, V. T., 1995. *Stratigraphy and Paleoenvironments of Late Quaternary Valley Fills on the Southern High Plains*. Boulder: Geological Society of America. GSA Memoir, Vol. 186.

Holliday, V. T., 2004. *Soils in Archaeological Research*. New York: Oxford University Press.

Holliday, V. T., Hoffecker, J. F., Goldberg, P., Macphail, R. I., Forman, S. L., Anikovich, M., and Sinitsyn, A., 2007. Geoarchaeology of the Kostenki-Borshchevo Sites, Don River Valley, Russia. *Geoarchaeology*, **22**(2), 181–228.

Holliday, V. T., Huckell, B. B., Weber, R. H., Hamilton, M. J., Reitze, W. T., and Mayer, J. H., 2009. Geoarchaeology of the Mockingbird Gap (Clovis) site, Jornada del Muerto, New Mexico. *Geoarchaeology*, **24**(3), 348–370.

Houben, P., 2007. Geomorphological facies reconstruction of Late Quaternary alluvia by the application of fluvial architecture concepts. *Geomorphology*, **86**(1–2), 94–114.

Huckleberry, G., and Duff, A. I., 2008. Alluvial cycles, climate, and puebloan settlement shifts near Zuni Salt Lake, New Mexico, USA. *Geoarchaeology*, **23**(1), 107–130.

Humphrey, J. D., and Ferring, C. R., 1994. Stable isotopic evidence for latest Pleistocene and Holocene climatic change in north-central Texas. *Quaternary Research*, **41**(2), 200–213.

Kesel, R. H., 2008. A revised Holocene geochronology for the Lower Mississippi Valley. *Geomorphology*, **101**(1–2), 78–89.

Knox, J. C., 1983. Responses of river systems to Holocene climates. In Wright, H. E., Jr. (ed.), *Late- Quaternary Environments of the United States*. Minneapolis: University of Minnesota Press. The Holocene, Vol. 2, pp. 26–41.

Kraus, M. J., and Brown, T. M., 1988. Pedofacies analysis: a new approach to reconstructing ancient fluvial sequences. In Reinhardt, J., and Sigleo, W. R. (eds.), *Paleosols and Weathering Through Geologic Time: Principles and Applications*. Boulder: Geological Society of America. GSA Special Paper, Vol. 216, pp. 143–152.

Kvamme, K. L., 2001. Current practices in archaeogeophysics: magnetics, resistivity, conductivity, and ground-penetrating radar. In Goldberg, P., Holliday, V. T., and Ferring, C. R. (eds.), *Earth Sciences and Archaeology*. New York: Kluwer Academic/Plenum, pp. 353–384.

Leopold, L. B., 1994. *A View of the River*. Cambridge, MA: Harvard University Press.

Lewin, J., 1978. Floodplain geomorphology. *Progress in Physical Geography*, **2**(3), 408–437.

Lewin, J., and Macklin, M. G., 2003. Preservation potential for Late Quaternary river alluvium. *Journal of Quaternary Science*, **18**(2), 107–120.

Lu, H., Burbank, D. W., and Li, Y., 2010. Alluvial sequence in the north piedmont of the Chinese Tian Shan over the past 550 kyr and its relationship to climate change. *Palaeogeography Palaeoclimatology Palaeoecology*, **285**(3–4), 343–353.

Macklin, M. G., and Lewin, J., 2008. Alluvial responses to the changing Earth system. *Earth Surface Processes and Landforms*, **33**(9), 1374–1395.

Macklin, M. G., Fuller, I. C., Lewin, J., Maas, G. S., Passmore, D. G., Rose, J., Woodward, J. C., Black, S., Hamlin, R. H. B., and Rowan, J. S., 2002. Correlation of fluvial sequences in the Mediterranean basin over the last 200 ka and their relationship to climate change. *Quaternary Science Reviews*, **21**(14–15), 1633–1641.

Macphail, R. I., and Cruise, J., 2001. The soil micromorphologist as team player: a multianalytical approach to the study of European microstratigraphy. In Goldberg, P., Holliday, V. T., and Ferring, C. R. (eds.), *Earth Sciences and Archaeology*. New York: Kluwer Academic/Plenum, pp. 241–267.

Mandel, R. D., 1995. Geomorphic controls of the Archaic record in the Central Plains of the United States. In Bettis, E. A., III (ed.), *Archaeological Geology of the Archaic Period in the United States*. Boulder: Geological Society of America. GSA Special Paper, Vol. 297, pp. 37–66.

Mandel, R. D., 2008. Buried paleoindian-age landscapes in stream valleys of the central plains, USA. *Geomorphology*, **101**(1–2), 342–361.

Mandel, R. D., and Bettis, E. A., III, 2001. Use and analysis of soils by archaeologists and geoscientists: a North American perspective. In Goldberg, P., Holliday, V. T., and Ferring, C. R. (eds.), *Earth Sciences and Archaeology*. New York: Kluwer Academic/Plenum, pp. 173–204.

Marder, O., Malinsky-Buller, A., Shahack-Gross, R., Ackermann, O., Ayalon, A., Bar-Matthews, M., Goldsmith, Y., Inbar, M., Rabinovich, R., and Hovers, E., 2011. Archaeological horizons and fluvial processes at the Lower Paleolithic open-air site of Revadim (Israel). *Journal of Human Evolution*, **60**(4), 508–522.

Miall, A. D., 1992. Alluvial deposits. In Walker, R. G., and James, N. P. (eds.), *Facies Models, Response to Sea Level Change*. St. John's: Geological Association of Canada, pp. 119–142.

NACSN (North American Commission on Stratigraphic Nomenclature), 2004. North American Stratigraphic Code. *American Association of Petroleum Geologists Bulletin*, **89**(11), 1547–1591.

Needham, S., and Macklin, M. G., 1992. *Alluvial Archaeology in Britain*. Oxford: Oxbow Books.

Nials, F. L., Gregory, D. A., and Hill, J. B., 2011. The stream reach concept and the macro-scale study of riverine agriculture in arid and semiarid environments. *Geoarchaeology*, **26**(5), 724–761.

Noller, J. S., 2001. Archaeoseismology: shaking out the history of humans and earthquakes. In Goldberg, P., Holliday, V. T., and Ferring, C. R. (eds.), *Earth Sciences and Archaeology*. New York: Kluwer Academic/Plenum, pp. 143–170.

Nordt, L. C., 2001. Stable carbon and oxygen isotopes in soils: applications for archaeological research. In Goldberg, P., Holliday, V. T., and Ferring, C. R. (eds.), *Earth Sciences and Archaeology*. New York: Kluwer Academic/Plenum, pp. 419–448.

Patnaik, R., Chauhan, P. R., Rao, M. R., Blackwell, B. A., Skinner, A. R., Sahni, A., Chauhan, M. S., and Khan, H. S., 2009. New geochronological, paleoclimatological, and archaeological data from the Narmada Valley hominin locality, Central India. *Journal of Human Evolution*, **56**(2), 114–133.

Patton, P. C., and Schumm, S. A., 1981. Ephemeral-stream processes: implications for studies of Quaternary valley fills. *Quaternary Research*, **15**(1), 24–43.

Phillips, J. D., 2011. Universal and local controls of avulsions in southeast Texas rivers. *Geomorphology*, **130**(1–2), 17–28.

Potts, R., Behrensmeyer, A. K., and Ditchfield, P., 1999. Paleolandscape variation and Early Pleistocene hominid activities: members 1 and 7, Olorgesailie Formation, Kenya. *Journal of Human Evolution*, **37**(5), 747–788.

Rapp, G. R., and Hill, C. L., 1998. *Geoarchaeology: The Earth-Science Approach to Archaeological Interpretation*. New Haven: Yale University Press.

Reineck, H.-E., and Singh, I. B., 1980. *Depositional Sedimentary Environments*, 2nd edn. Berlin: Springer.

Ritter, D. F., Kochel, R. C., and Miller, J. R., 2011. *Process Geomorphology*, 5th edn. Long Grove: Waveland.

Rosen, A. M., 1997. The geoarchaeology of Holocene environments and land use at Kazane Höyük, S.E. Turkey. *Geoarchaeology*, **12**(4), 395–416.

Rosen, A. M., 2008. The impact of environmental change and human land use on alluvial valleys in the loess plateau of China during the Middle Holocene. *Geomorphology*, **101**(1–2), 298–307.

Schuldenrein, J., 2007. A reassessment of the Holocene stratigraphy of the Wadi Hasa terrace and Hasa Formation, Jordan. *Geoarchaeology*, **22**(6), 559–588.

Schumm, S. A., 1977. *The Fluvial System*. New York: Wiley.

Semaw, S., Rogers, M. J., Quade, J., Renne, P. R., Butler, R. F., Domínguez-Rodrigo, M., Stout, D., Hart, W. S., Pickering, T., and Simpson, S. W., 2003. 2.6-million-year-old stone tools and associated bones from OGS-6 and OGS-7, Gona, Afar, Ethiopia. *Journal of Human Evolution*, **45**(2), 169–177.

Sharp, W. D., Ludwig, K. R., Chadwick, O. A., Amundson, R., and Glaser, L. L., 2003. Dating fluvial terraces by ^{230}Th/U on pedogenic carbonate, Wind River Basin, Wyoming. *Quaternary Research*, **59**(2), 139–150.

Sikes, N. E., and Ashley, G. M., 2007. Stable isotopes of pedogenic carbonates as indicators of paleoecology in the Plio-Pleistocene (Upper Bed I), western margin of the Olduvai Basin, Tanzania. *Journal of Human Evolution*, **53**(5), 574–594.

Stafford, C. R., and Creasman, S. D., 2002. The hidden record: late Holocene landscapes and settlement archaeology in the Lower Ohio River Valley. *Geoarchaeology*, **17**(2), 117–140.

Törnqvist, T. E., and Bridge, J. S., 2002. Spatial variation of overbank aggradation rate and its influence on avulsion frequency. *Sedimentology*, **49**(5), 891–905.

Van Andel, T. H., and Tzedakis, P. C., 1996. Paleolithic landscapes of Europe and environs, 150,000–25,000 years ago: an overview. *Quaternary Science Reviews*, **15**(5–6), 481–500.

Van De Wiel, M. J., Coulthard, T. J., Macklin, M. G., and Lewin, J., 2011. Modelling the response of river systems to environmental change: progress, problems and prospects for palaeo-environmental reconstructions. *Earth-Science Reviews*, **104** (1–3), 167–185.

Wagner, D. P., and McAvoy, J. M., 2004. Pedoarchaeology of Cactus Hill, a sandy Paleoindian site in southeastern Virginia, U.S. A. *Geoarchaeology*, **19**(4), 297–322.

Waters, M. R., 1992. *Principles of Geoarchaeology: A North American Perspective*. Tucson: University of Arizona Press.

Waters, M. R., 2000. Alluvial stratigraphy and geoarchaeology in the American Southwest. *Geoarchaeology*, **15**(6), 537–557.

Waters, M. R., Forman, S. L., Jennings, T. A., Nordt, L. C., Driese, S. G., Feinberg, J. M., Keene, J. L., Halligan, J., Lindquist, A., Pierson, J., Hallmark, C. T., Collins, M. B., and Wiederhold, J. E., 2011. The Buttermilk Creek Complex and the origins of Clovis at the Debra L. Friedkin Site, Texas. *Science*, **331**(6024), 1599–1603.

Wells, L. E., 2001. A geomorphological approach to reconstructing archaeological settlement patterns based on surficial artifact distribution. In Goldberg, P., Holliday, V. T., and Ferring, C. R. (eds.), *Earth Sciences and Archaeology*. New York: Kluwer Academic/Plenum, pp. 107–141.

Wiant, M. D., Hajic, E. R., and Styles, T. R., 1983. Napoleon Hollow and Koster Site stratigraphy: implications for Holocene landscape evolution and studies of Archaic period settlement patterns in the Lower Illinois River Valley. In Phillips, J. L., and Brown, J. A. (eds.), *Archaic Hunters and Gatherers in the American Midwest*. New York: Academic, pp. 147–164.

Wood, W. R., and Johnson, D. L., 1978. A survey of disturbance processes in archaeological site formation. In Schiffer, M. B. (ed.), *Advances in Archaeological Method and Theory*. New York: Academic, Vol. 1, pp. 315–381.

Zaim, Y., Ciochon, R. L., Polanski, J. M., Grine, F. E., Bettis, E. A., III, Rizal, Y., Franciscus, R. G., Larick, R. R., Heizer, M., Aswan, Eaves, K. L., and Marsh, H. E., 2011. New 1.5 million-year-old *Homo erectus* maxilla from Sangiran (Central Java, Indonesia). *Journal of Human Evolution*, **61**(4), 363–376.

Cross-references

Big Eddy Site, Missouri
Cactus Hill, Virginia
Chronostratigraphy
Colluvial Settings
Eolian Settings: Loess
Eolian Settings: Sand
Geomorphology
Koster Site, Illinois
Optically Stimulated Luminescence (OSL) Dating

Oxygen Isotopes
Paleoenvironmental Reconstruction
Pre-Clovis Geoarchaeology
Sedimentology
Site Formation Processes
Site Preservation
Soil Geomorphology
Soil Micromorphology
Soils
U-Series Dating

AMINO ACID RACEMIZATION

Kirsty Penkman
BioArCh, Department of Chemistry, University of York, York, UK

Synonyms

Amino acid geochronology; Amino acid racemization; Aminostratigraphy

Definitions

Amino acid racemization: a spontaneous reaction describing the interconversion between the chiral forms of an amino acid.

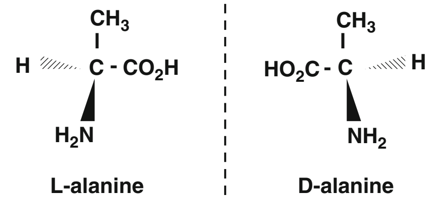
Chiral: describes molecules that may exist as mirror images of themselves that are nonsuperimposable; such molecules exhibit chirality.

Enantiomer: one of a pair of nonsuperimposable mirror images; also called an optical isomer.

Stereoisomer: molecules that possess the same elemental composition but different three-dimensional arrangements of atoms.

Diastereomer: a stereoisomer that is not a mirror image, that is, not an enantiomer.

Amino acids are the building blocks of proteins. They are found in all living tissues and can be preserved in fossil biominerals such as bone, teeth, and shells. The 20 naturally occurring amino acids all have a central carbon atom (the α-C) with four attached groups: an amino group (NH_3), a carboxylic acid group (COOH), hydrogen (H), and a side chain (R) that defines the type of amino acid. In glycine, the side chain is H, but for all other amino acids, the α-C has four different groups. The four distinct groups connected by single bonds make the α-C a chiral center, meaning that it can exist as two stereoisomers: the *levo* (L-form) and *dextro* (D-form), named after the optical activity of glyceraldehyde. Such stereoisomers are enantiomers because they are not only chemically identical, but they are also nonsuperimposable mirror images of each other (Figure 1). In living organisms, proteins are almost exclusively made from the L-form. However, this artificial dominance of the one form is unstable, so after death, a spontaneous reaction occurs to redress the balance. The extent of amino acid racemization (AAR) is recorded as a D/L value; AAR continues until a dynamic equilibrium is reached (usually D/L = 1). Depending on the amino acid, this process can take thousands or millions of years and therefore is applicable over Quaternary timescales. First applied to fossil shells (Hare and Abelson, 1968), AAR geochronology measures the extent of this degradation in fossils as an index of relative age (an aminostratigraphy), which can provide calibrated ages in combination with known-age samples or detailed temperature records.



Amino Acid Racemization, Figure 1 L- and D-amino acid structure of alanine. Bonds depicted as hatched wedges go into the page, while those that are thick wedges come out of the page. The central carbon atom has four different functional groups attached to it; it is therefore a chiral center, and two chemically identical, but nonsuperimposable, mirror images can occur: L- and D-alanine.

Protein degradation consists of a series of chemical reactions that are dependent not only on time but also on environmental factors. The original protein composition is important, so AAR will occur at different rates in different species, precluding direct comparison in most cases. Environmental factors (e.g., temperature, pH, availability of water) can also affect AAR rates, leading to a focus on analyzing "closed-system" protein from fossil samples (Towe, 1980). A chemically protected organic fraction found in mollusk and egg shells (the "intracrystalline" fraction) appears to be shielded from the environment and does not lose any material through leaching, meaning that the protein degradation within this fraction is solely time and temperature dependent and therefore predictable. This technique has been particularly successful in dating carbonate fossils (shells, eggshells, foraminifera, ostracods). Advances in chromatography, preparative methods, and choice of material for dating have resulted in greatly improved temporal resolution, demonstrating the technique's potential for developing regional Quaternary chronologies around the world (e.g., Parfitt et al., 2005; Wehmiller, 2012).

Bibliography

Hare, P. E., and Abelson, P. H., 1968. Racemization of amino acids in fossil shells. *Yearbook of the Carnegie Institution of Washington*, **66**, 526–528.

Parfitt, S. A., Barendregt, R. W., Breda, M., Candy, I., Collins, M. J., Coope, G. R., Durbidge, P., Field, M. H., Lee, J. R., Lister, A. M., Mutch, R., Penkman, K. E. H., Preece, R. C., Rose, J., Stringer, C. B., Symmons, R., Whittaker, J. E., Wymer, J. J., and Stuart, A. J., 2005. The earliest record of human activity in northern Europe. *Nature*, **438**, 1008–1012.

Towe, K. M., 1980. Preserved organic ultrastructure: an unreliable indicator for Paleozoic amino acid biogeochemistry. In Hare, P. E., Hoering, T. C., and King, K., Jr. (eds.), *Biogeochemistry of Amino Acids*. New York: Wiley, pp. 65–74.
Wehmiller, J. F., 2012. United States Quaternary coastal sequences and molluscan racemization geochronology – what have they meant for each other over the past 45 years? *Quaternary Geochronology*, doi:10.1016/j.quageo.2012.05.008.

ANALYSIS OF CARBON, NITROGEN, PH, PHOSPHORUS, AND CARBONATES AS TOOLS IN GEOARCHAEOLOGICAL RESEARCH

Michael F. Kolb
Strata Morph Geoexploration, Inc, Sun Prairie, WI, USA

Introduction

In the context of archaeological research soil/deposit chemical analysis should be viewed as an additional data set or tool for interpreting the archaeological record. Because chemical signatures are not exclusively anthropogenic (they are not uniquely of human construction like artifacts), there is always a non-anthropogenic component or effect. Human activity either indirectly modifies a soil's chemical characteristic, as with pH, or it directly adds or subtracts material creating an anomaly by altering the amount of carbon, phosphorus, nitrogen, or carbonates in the deposits. Anomalies can only be detected if there is baseline data that characterizes the deposits prior to human intervention. This is accomplished by setting up control sampling locations or, if that is not possible, obtaining background data from preexisting sources (e.g., from sources like Shacklette and Boerngen, 1984). Interpretation of chemical data in archaeological contexts involves comparisons to control samples and an understanding of the evolution and maintenance of the anthropogenic soil anomaly (Carr, 1982). This is no small feat given the complexity of temporal and spatial occupation histories at many archaeological sites and the complex pedogenic response over time to anthropogenic activity.

Because this entry is about soil chemical analysis in archaeology, it seems appropriate to define soil from a soil chemist's perspective:

> Soils are multi-component, open, biogeochemical systems containing solids, liquids and gases. That they are open systems means they exchange both matter and energy with the surrounding atmosphere, biosphere, and hydrosphere. These flows of matter and energy to or from soil are highly variable in time and space but they are the essential fluxes that cause the development of soil profiles and govern patterns of soil fertility. (Sposito, 1989, 3)

The definition emphasizes that soils are open systems that adjust to variations in input. Knowing or hypothesizing about those adjustments after anthropogenic input over archaeological time scales is important for interpreting chemical data from archaeological contexts. The state factor's model of soil formation first developed by Jenny (1941) and advanced in geoarchaeology by Holliday (1994, 2004a) is an excellent conceptual framework for interpreting soil chemical data in archaeological contexts. The model consists of five external factors that govern soil formation. They are (1) climate, (2) organisms (plants and animals), (3) relief (landscape position), (4) parent material (anthropogenic and non-anthropogenic deposits), and (5) time. Both these factors and soil-forming processes vary, resulting in changes in soil morphology, hydrology, and chemistry. The human animal can be considered with all the other organisms involved in soil formation or, perhaps, more appropriately as the sixth factor. Human populations, although they are just a player in the ecological drama, are the dominant one. They modify all of the factors of soil formation in major ways at scales from a single dwelling to the global climate (Hooke et al., 2012).

Control sampling

Chemical analysis in geoarchaeology is comparative so it demands two or more data sets to be of much analytical use. Control samples should be taken in the field and analyzed to determine the background or natural level of the chemical of interest. This is equivalent to analyzing blanks in the laboratory, a standard and necessary procedure. The point of control sampling is to determine the non-anthropogenic or natural background chemistry of the soil off-site, and the state factor model is again a good conceptual guide. Thus, it is best to pick landscape positions off-site, where all of the state factors are similar to the sampling loci on the site. Multiple control locations may be necessary. In many situations (e.g., modern or ancient urban areas), finding a location that has not been previously utilized or occupied or that you know has not been utilized or occupied is difficult but should be attempted. Certainly a number of authors have advocated using control samples or have effectively used control samples in their research (see Proudfoot, 1976; White, 1978; Bakkevig, 1980; Carr, 1982; Sandor, 1992; Entwistle et al., 2000; Wells et al., 2000; Holliday, 2004a). In addition all samples should be analyzed using the same techniques/procedures and by the same laboratory to reduce unnecessary sources of error and uncertainty (see Holliday and Stein, 1989; Holliday et al., 2004c).

In many geoarchaeological investigations that use soil chemistry, a suite of chemical analyses is used to address research questions. For this reason geoarchaeological applications will follow the discussion of each of the chemical techniques.

Carbon/organic matter

Sources and transformations in soils and deposits

Carbon occurs in soils in organic and inorganic forms (Stevenson and Coles, 1999). Organic forms occur as living plants and animals and as the by-products of the decomposition of plants and animals referred to collectively as the soil's organic matter fraction (SSSA, 1997). Inorganic forms can also be added to the soil by plants that contain crystals of calcium oxalate or opaline silica (Weiner et al., 2002; Piperno, 2006; Prychid et al., 2008). Calcium oxalates would contribute some carbon to a total carbon assay. However, most inorganic carbon is derived from the parent material (carbonate rocks and dust) (Birkeland, 1984; Nelson and Sommers, 1982). In non-calcareous soils almost all of the carbon is in the organic fraction of the soil (Nelson and Sommers, 1982). Carbon is a part of organic matter that is introduced into the soil by natural process and anthropogenically as plant tissue with a more minor contribution from animal tissue. Plant residue consists of 25 % solids that are made up of carbon, oxygen, hydrogen, and ash (Brady, 1974). The ash contains the macronutrients (phosphorus, potassium, calcium, magnesium, and sulfur) and micronutrients (zinc, iron, copper, boron, manganese, and molybdenum) as well as minor trace elements (Brady, 1974). These are relevant to studies of soil chemistry at archaeological sites as they form part of the anthropogenic and natural chemical load in soils and deposits. As soon as organic matter is added to the soil, it begins to decay. The rate of decay and the products of decomposition depend on the soil environment (Brady, 1974). In turn, the nature and strength of any anthropogenic anomaly depend on the nature and intensity of occupation and the soil-forming environment (Carr, 1982).

Anthropogenic additions, subtractions, and transformations

Human populations are major players in cycling organic material in the environment. The organic carbon fraction is of interest in geoarchaeological studies because it is a component of building material (wood and adobe), food, waste, and a by-product of food preparation, material processing, and heating (e.g., charcoal) at human habitations and ultimately in archaeological deposits. It is continually moved from place to place in the process of food production, settlement construction, and waste disposal. As a result, it is added to the soil, directly and indirectly, in the form of waste from a variety of activities in and around settlements, for example, the dark earths in Amazonia (McCann et al., 2001) and Europe (Chapter "FTIR" in Courty et al., 1989). And it is removed from the soil in places where farming or resource extraction (removal of tress or crops), for example, occurs. The most significant anthropogenic transformation of organic matter is by burning. This reduces organic matter to the much more decay-resistant and carbon-rich charcoal. In chemical analyses charcoal is measured as a part of the organic matter or total carbon fraction of the soil. It can also be used, for example, to determine the species (Asouti and Austin, 2005; Marguerie and Hunot, 2007) of wood being exploited for fuel and building material or if the wood was collected dead or alive (Moskal-del Hoyo et al., 2010). Charcoal is only relatively stable. It can be degraded and disseminated into small particles in alkaline soils (Dufraisse, 2006; Braadbaart et al., 2009) and can be attached by soil fauna and flora (Thery-Parisot et al., 2010). Reduced particle size has implication for site formation processes and chronology as the charcoal is more mobile in the soil profile. Stein (1992) provides a general summary of organic matter in archaeological contexts.

Analytical methods

Total carbon in soils can be determined by wet or dry combustion techniques (Nelson and Sommers, 1982). Note this technique measures all forms of both the organic and inorganic carbon in the soil. The basic principle is to drive off and capture the CO_2 and then measure the amount captured gravimetrically or titrimetrically. This is generally done with automated laboratory instruments designed for carbon analysis (see Nelson and Sommers (1982) for examples and procedures). Another measure of soil organic matter is near-infrared reflectance spectroscopy (see entry "Anthrosols" by Woods this volume).

The most commonly used procedures to determine organic carbon are Walkley-Black (Nelson and Sommers, 1982; Singer and Janitzky, 1986) and loss-on-ignition (Dean, 1974) techniques. With Walkley-Black the sample is digested in dichromate and sulfuric acid, and the amount of carbon is determined by titration or colorimetrically. This procedure uses strong acids and needs a laboratory setup to do the digestion.

Loss-on-ignition is a simpler procedure, is as accurate (Dean, 1974) as Walkley-Black, and can also be used to determine carbonate in the sample. The procedure consists of placing oven-dried soil in a small pre-weighed crucible and heating it in a muffle furnace to 550 °C, cool to room temperature in a desiccator and reweighed. The difference is the amount of organic carbon ignited. The sample and crucible are placed in the oven and reheated to a higher temperature to determine the carbonate content (see section on carbonates below). The number of samples that can be done at one time is only limited by the size of the muffle furnace. Loss-on-ignition can also be done using automated thermogravimetric analyzers, which can process many samples at one time with direct computerized calculations, producing immediate tables and plots of results.

Nitrogen

Most nitrogen in the soil is associated with organic matter or soil humus (Brady, 1974) that can be slowly released by the actions of microorganisms and made available to plants. The soluble ammonium and nitrate is readily available to plants but is also easily leached from the soil. Because nitrogen compounds are rapidly fixed (unavailable to plants) and mobile (available but easily leached), heavily cropped soils need a constant artificial supply of nitrogen fertilizer especially in modern mechanized agricultural systems.

Sources and transformations in soils and deposits

Inputs of nitrogen to the soil come from addition of organic matter during the process of plant growth and decay, fixed by microorganisms from the atmosphere, and brought in to the soil in the form of ammonium and nitrate salts by precipitation (Brady, 1974). Once in the soil nitrogen is generally immobile or fixed except for small amounts of inorganic nitrogen in the form of nitrates and ammonium nitrates. Some ammonium nitrogen is also fixed in the lattices of clay minerals where it is very slowly available to plants during weathering. These later forms are available to plants and are mobile in soil water. Most nitrogen is rapidly cycled (Stevenson and Coles, 1999), a process whose rate depends on soil conditions (factors) especially climate.

Anthropogenic additions, subtractions, and transformations

Human activity alters the nitrogen cycle by adding organic matter (waste and garbage) or fertilizer/manure in some places and removing it in others (movement of plants and building material to settlements). Because nitrogen is added to the soil along with carbon and other elements when disposing of plant or animal waste or fertilizing agricultural fields, it creates an anomaly that is closely associated with organic matter (carbon) anomalies. As organic matter breaks down, much of the nitrogen is rapidly volatilized and lost to the atmosphere or becomes mobile in the soil water (Brady, 1974). The remaining nitrogen is fixed by clay mineral or combines with soil organic matter. Because nitrogen cycles rapidly, it may not maintain a anthropogenic anomaly over long time spans, so it is not a good indicator of anthropogenic load (Holliday, 2004a) except, perhaps, on young archaeological sites (Woods, 1982) or in arid areas (Homberg et al., 2005).

Analytical methods

There are two types of analysis that deal with total nitrogen: Kjeldahl wet combustion and Dumas dry combustion (Bremner and Mulvaney, 1982). In the Kjeldahl analysis the nitrogen in the samples is converted to ammonia ($NH_4^+{-}N$) by heating in sulfuric acid in the presence of catalysts. The amount of nitrogen is determined by measuring the amount of NH_3 liberated from the digest when distilled in an alkali. Dumas analysis involves heating the sample with CuO and exposing the liberated gas to hot Cu to reduce the nitrogen oxides and then to CuO to convert the CO to CO_2. The $N_2{-}CO_2$ mixture is then collected and exposed to a concentrated alkali that removes the CO_2, and then the volume of N_2 is measured. Both methods are complex and have recovery problems that researchers should be aware of before choosing a procedure (see Bremner and Mulvaney, 1982). Automated N analyzers are capable of processing samples relatively rapidly and produce results comparable to the wet chemistry methods (Thomas et al., 1967; Schuman et al., 1972).

pH

The measure of the activity of ionized H (H+) in the soil solution is called pH (Mc Lean, 1982). It is one of the most indicative measures of soil chemistry (Boul et al., 1989) and is important in determining (after Mc Lean, 1982) the (1) solubility and hence mobility of compounds in the soil, (2) the bonding of ions to exchange sites, (3) activity of microorganisms, and (4) availability of plant nutrients. The pH scale ranges from 1 (most acidic) to 14 (basic), 7 being neutral.

Sources and transformations in soils and deposits

Soil pH is not an element or compound that can be added or subtracted from the soil but instead is a condition of the aqueous phase of the soil environment that is very dependent on the interaction and evolution of the soil-forming factors. Many chemical reactions, weathering trajectories, and soil–plant relationships are pH dependent. Because soil water system is open, external inputs of water (including its dissolved constituents) and organic and inorganic particles – both natural and anthropogenic – can rapidly change the soil pH (Sposito, 1989) and therefore the pedogenic trajectory and the maintenance of the anthropogenic anomaly.

Anthropogenic additions, subtractions, and transformations

The degree to which soil pH is modified by anthropogenic additions depends on the initial soil pH, buffering, and pedogenic context. Anthropogenic modifications of pH are direct and indirect. Direct addition of wood ash, limestone (especially burnt), and shell maintains alkalinity (Cook and Heizer, 1965). Addition of organic matter indirectly lowers pH because the decay of OM produces acids (Brady, 1974). Soil pH is an important parameter for predicting the degree of bone preservation, including bone proteins used in DNA analysis, and metal and charcoal preservation in archaeological deposits (Tylecote, 1979; Gordon and Buikstra, 1981; Pate and Hutton, 1988; Nielsen-Marsh et al., 2007; Braadbaart et al., 2009; Adler et al., 2011). Sheppard and Pavlish (1992) have shown that among other soil chemical variables, pH is important in the weathering of chert. Soil pH is also one factor in determining the potential for preservation of phytoliths (see Piperno 2006; Cabanes et al., 2011). In most geoarchaeological investigations that use soil chemistry, pH is one of a suite of chemical analyses used to characterize the soil as background for interpretations.

Analytical methods

Determination of pH is accomplished using either colorimetric or electrometric techniques (Mc Lean, 1982). Colorimetric techniques use dyes or acid–base indictors that react by changing color in different pH environments. In its simplest form the electrometric technique consists of a glass electrode that measures the hydrogen ion activity and a reference electrode that completes a circuit so voltage can be measured (Mc Lean, 1982). The pH is typically measured in a 1:1 soil–water mixture (see Janitzky 1986 or Mc Lean, 1982). Many portable colorimetric and electrometric systems are available for field measurement of pH.

Phosphorus

The most widely used soil chemical technique in archaeological research is certainly the analysis of phosphorus. This is because humans are very proficient at concentrating P in and around places where they live and much of the P added to soils is considered fixed (Brady, 1974; Walker and Syers, 1976). The source of the P is the plant and animal remains and waste left at sites that ultimately ends up in the soil. The association of high soil phosphorus levels and human settlements was first documented in the 1920s by Swedish soil scientist, G. Arrhenius (see Eidt, 1985 or Wells et al., 2000 for brief history). Since that time, P analysis has been used in many archaeological contexts to aid in determining site and feature boundaries, intra-site activity areas, intensity of occupation, and types of land use (for recent studies, see Barba et al., 1996; Parnell et al., 2001; Fernández et al. 2002; Barba, 2007; Middleton et al., 2010; Roos and Nolan, 2012).

There are a number of reviews of archaeological/geoarchaeological research using phosphorus that should be consulted as an initial source before developing a research strategy that includes P analysis. The most recent and most thorough reviews can be found in Holliday (2004b) and Holliday and Gartner (2007). They cover basic chemistry, common methods of extracting and measuring soil P, and the use of soil P in chronosequence studies. Proudfoot (1976) provides a general review of the extraction procedures and chemistry of P in soils, anthropogenic additions, and sampling issues as well as an example of P analysis from an archaeological site in Britain. Bakkevig (1980) provides more of a cautionary tale pointing out the importance of understanding the natural P background and the geomorphic context of any sampling site. White (1978) also stresses the importance of having background data.

Sources and transformations in soils and deposits

The chemistry of soil P is complicated, in part because the P anions can bind with a number of cations in the soil to form compounds where the P bond varies in strength. P chemistry is strongly pH dependent which in turn is dependent on the soil factors at a particular site and on the natural and anthropogenic evolution of the site. A detailed explanation of P chemistry is beyond the scope of this entry, so P will be covered in a simple way under the heading of additions, subtractions, and transformation.

Almost all of the phosphorus in the soil system ultimately came from weathering of the inorganic P minerals (primarily apatite) in the soil parent material (Walker and Syers, 1976). The soluble P is taken up by plants, and upon death, they add organic matter to the soil. Once the system is established, most of the soil phosphorus is contained in soil organic matter (Brady, 1974). Soil microorganisms mineralize the organic forms of P to soluble inorganic forms ($H_2PO_4^-$, HPO_4^-) that are available to plants and can be leached out of the soil with the soil water. These latter processes are ways P can leave the soil, although on landscapes that are not cropped, the P is recycled. Of course weathering continues and small amounts of P still enter the soil from that source.

Most of the phosphate anions that enter the soil quickly form calcium (Ca), aluminum (Al), or iron (Fe) phosphates. Which compounds form depends on the soil pH and the amount and kind of each cation present. Brady (1974) divides P compounds in the soil into three major groups: (1) readily available phosphates that are generally water soluble (non-occluded P); (2) slowly available P including newly formed Al, Fe, and Mn phosphates, Ca phosphates, and mineralized organic phosphates; and (3) very slowly available phosphates of Fe, Al, and Mn, apatites and stable organic phosphates. His view of P is from the perspective of agronomy and soil science, where most basic research on P in soils has taken place. Laboratory analyses designed to study P in soils reflect the kinds of P found in soil (see below). Anthropogenic addition of P to the soil is also held at different location in the soil so to detect the anthropogenic anomalies P must be extracted either totally or differentially by chemically targeting the different phosphate compounds.

Soil phosphorus is only relatively stable over time because as soil factors change in response to environmental change and pedogenic processes adjust, P can be removed from the soil system or reorganized within the soil (see Walker and Syers, 1976; Tiessen et al., 1984; Roberts et al., 1985). On geomorphically unstable landscape facets, where erosion or deposition is occurring, the retention of P and the post-depositional evolution of the any anthropogenic P anomaly change.

Anthropogenic additions, subtractions, and transformations

Anthropogenic sources of P come from domestic refuse, food waste, plant and animal remains, human bodies (especially bones), human and animal excrement, and wood ash (Cook and Heizer, 1965; Carr, 1982; Woods, 1982). Human populations are a factor in the P cycle and as such alter the process of P cycling. These alterations can be detected in the soils on archaeological sites.

Analytical methods

Analysis of P in soils has two stages. The first stage is extracting the P from the soil (Olsen and Sommers, 1982; Meixner, 1986a). The extractant used depends on which form or forms of P are being targeted. The second stage is the determination of the amount of P in the extractant. This is accomplished by using a colorimetric method. In P fractionation multiple extractants are used in sequence to determine the different forms of P in the soils.

Spot test or ring test is a qualitative measure of P that can be done in the field with simple tools and reagents (Gundlach, 1961; Eidt, 1973; Woods, 1975). The test uses a weak acid extractant to measure the available P. Color is developed on filter paper based on a qualitative scheme (see Eidt, 1973). The advantage of the spot test is fast, low-cost results, but the disadvantages are qualitative non-reproducible results (Holliday, 2004b).

Available P refers to techniques that extract the water-soluble P and weakly held P fractions (Olsen and Somers, 1982). This involves extracting the P with weak acid and developing color intensity that can be read in a spectrometer. Available P types are often referred to by the name of the person who developed them such as Olsen P, Bray 1, or Mehlich II tests. They are differentiated because they use different extractants. Available P can also be done in the field with a portable spectrometer (see Terry et al., 2000).

Phosphate fractionation is the process of sequentially extracting P beginning with the most weakly bound P using extractants that target specific P compounds (Olsen and Somers, 1982; Meixner, 1986b). As many as eight different fractions, grouped into non-occluded P (three extractions), occluded P (three extractions), calcium bond P (one extraction), and organic P (one extraction), can be involved (see Meixner, 1986b). Most P fractionations in geoarchaeological applications use a three-fraction extraction sequence developed by Eidt (1977). This is an intensive wet chemistry procedure that targets the weakly bound Fe and Al-P and the reabsorbed Ca-P as fraction I (Eidt, 1977). Occluded P is fraction II and calcium P and apatite are fraction III.

Total P can be determined by using very strong acids to completely digest the soil, and P is measured colorimetrically (Olsen and Somers, 1982; Meixner 1986c). Total P can also be measured using ICP spectrometry, usually as one of a suite of elements. The ICP measures the P content so the type of P measured still depends on the extraction procedure.

Carbonates

The origin of carbonate in soils is either from eolian sources, inherited from calcareous parent material, or weathered from non-calcareous parent material (Birkeland, 1984). Pedogenesis results in carbonate accumulations in soils in arid and semiarid climate zones and in its removal from the soil system in humid and tropical climatic zones (Birkeland, 1984; Boul et al., 1989). Carbonates are often measured as a part of soil/deposit characterization by determining the presence or absence of free carbonate using a few drops of HCl or less often by laboratory analysis. Results are used to determine the presence or absence of an anthropogenic carbonate load by comparison of control samples or other regional soil data and, if carried a step further, to interpret the anthropogenic changes in the pedogenic trajectory relative to site formation processes. For example, carbonates can dominate the soil chemistry in part by their effect on pH which in turn affects artifact preservation, especially bone and shell, and the post-depositional evolution of any anthropogenic additions (e.g., see Weiner et al., 2002).

Sources and transformations in soils and deposits

The source of the carbonates in soil is atmospheric dust containing carbonate and Ca^{2+} ions (Machette, 1986; Birkeland, 1984) and carbonate in parent materials (limestone, gypsum, dolostone, loess, glacial deposits from carbonate terrain). Parent material weathering in non-calcareous soils cannot account for the large amount of carbonate in arid and semiarid soils (Birkeland, 1984). In arid and semiarid regions, pedogenic processes form calcic soil horizons (K horizons) (Birkeland, 1984; Machette, 1986). In humid and tropical soils with lower pH, the carbonate is disassociated and is leached out of the soil system or accumulates as minor secondary carbonates in the C horizon (Boul et al., 1989).

Anthropogenic additions, subtractions, and transformations

Anthropogenic additions that may increase the carbonate content in soils or lead to the formation of secondary carbonates are limestone and dolostone for cooking and, in some cases, pottery manufacturing and/or food processing, building material (plaster and stone), wood ash, and shell (Cook and Heizer, 1965; Woods, 1982; Schiegl et al., 1996). The age of the archaeological site, soil conditions, and landscape position are some factors that affect the post-depositional modification of anthropogenic carbonate additions. For example, physical and chemical processes during pedogenesis may destroy or fragment shell or carbonate rock adding secondary carbonate to the soil or removing it from the soil system entirely. Soil – geomorphic and stratigraphic – studies at archaeological sites record the soil carbonate status for characterization purposes with little geoarchaeological interpretations. Woods (1982) interprets the high carbonate levels in a midden in Illinois to be the result of the addition of ash to the midden. Indirectly human activity (e.g., land clearing and agriculture) that causes geomorphic instability may result in wind erosion, which could also add carbonate to soil.

Analytical methods

The simplest measure of the presence of carbonate in soil is to observe the strength of soil reaction to 10 % HCl. The strength of the reaction is measured by the violence of the effervescence. The more carbonate, the more violent the reaction.

The loss-on-ignition (LOI) (Dean, 1974) method is used to determine both OM and carbonate. A sample is placed in a furnace first to 550 °C to destroy the organic matter, cooled and weighed, then put back in the furnace and heated to 1,000 °C to drive off the CO_2 in the carbonate. The sample is cooled and weighed again to determine the percent carbonate. Dean (1974) compared the LOI method with acid extractions and then titration and with determination of total Ca with atomic absorption and found that they yielded very similar results. Thermogravimetric analyzers have now completely automated the above procedure.

In the acid neutralization method, the carbonates are dissolved in acid and the amount of carbonate is determined by titration (Nelson, 1982). The gravimetric method uses a Chittick apparatus to determine the volume of CO_2 evolved during acid digestion (Machette, 1986).

Geoarchaeological applications

The section on applications begins with examples of the use of phosphorus in geoarchaeological studies. Phosphorus data have been used as a tool in geoarchaeological investigations for nearly a century, and the literature is relatively extensive (see Eidt, 1985; Wells and Terry, 2007). The treatment below is not comprehensive and attempts to group the investigations by type. Chemical analyses, including phosphorus, are a part of a suite of measures used in the study of the Amazonian dark earths and are not included here (Glaser and Woods, 2004; see Woods this volume). Most investigations focus on the spatial distribution of P anomalies on the landscape surface within and around sites. The goal of these studies is to find site boundaries or to identify activity areas within sites. This involves examining both positive and negative P anomalies.

Skinner (1986) investigated P levels at five archaeological sites in Ohio. The goal of the investigation is to determine if P can identify anthropic soils and locate site boundaries determined by artifact distributions. Three different extraction techniques are compared for available P and one for total P. The conclusion is that the reliability of P as an anthrosol indicator depends on the geomorphic and pedogenic context specifically whether or not a soil/site was subject to inundation (i.e., located on a floodplain).

Roos and Nolan (2012) used available P (Mehlich II extraction) levels from 131 samples at a late prehistoric village site in Ohio to map intra-site activity areas. They were able to identify a ring midden and plaza using P data supported by magnetic data and artifact distributions.

Schuldenrein (1995) used soil chemistry (pH, OM, K, Ca, Mg) including available P, total P, and P fractionation, to detect activity areas at two sites in contrasting environments: the semiarid plains and humid temperate woodlands, both in the USA. Comparisons of control sample series with on-site and feature sample series indicate anthropogenic anomalies are present at both sites and is most strongly characterized by levels of P and K or P and selected other measures depending on the physical and cultural context. Plots of the three P fraction loadings on ternary diagrams are proposed as a graphic means of differentiating types of activity areas.

Woods (1982) found the following chemical trends at archaeological sites in Illinois. Carbon (organic matter) and nitrogen level were higher in midden soils than in control soils and both decreased in magnitude with depth. He found pH levels to be significantly more alkaline than control samples due to the large amount of wood ash in the middens that in effect neutralizes the acidifying effect of decaying organic matter. He also attributed carbonates in the middens to the addition of wood ash in an alkaline environment. P is high in the middens and absolute levels correlate with soil texture with P levels higher in clayey soils.

A number of interdisciplinary investigations have been conducted at the Piedras Negras site and surrounding modern settlements in Guatemala. These studies all use a field test procedure based on a Mehlich II acid extraction and measurement with colorimetry modified for use in relatively primitive field conditions (Terry et al., 2000; Wells et al., 2000; Parnell et al., 2001). The investigation identified a good correlation between P levels, density of ceramics, and boundaries of disposal areas. Fernandez et al., (2002) and Terry et al., (2004) investigated soil chemical signatures in modern settlements and a Mayan archaeological site to explore the relationship between chemical data (P, pH, Mg, Na, K, and trace elements) and household human activities. Phosphorus was high in areas of food processing, consumption, and disposal. Food preparation areas had high levels of P, Mg, and K and were more alkaline, while food consumption areas had high P and Na and were more acid. Traffic lanes had low P and refuse disposal areas have high P.

Dunning (1993) used total P to distinguish different types of land use and P fractionation to differentiate between agricultural and nonagricultural soils. High P levels are interpreted as areas that were gardens and likely fertilized and areas with depleted P as places of more intensive field agriculture.

Sandor (1992) compared the morphological and chemical characteristic of terraced cultivated soils and uncultivated soils at a 1,000–1,500-year-old prehistoric site in New Mexico, USA. Cultivated soils lost organic matter, N, and phosphorus (total and moderately available) and lowered pH. In contrast soils in terraced fields in Peru have elevated levels, relative to uncultivated soils, of total and available P, nitrate nitrogen (NO_2-N), total nitrogen, and organic carbon. Soil pH tended to be more acidic due to the increased organic matter. The chemical data, supplemented the archaeological evidence and soil morphological data, indicating the agricultural soils in New Mexico were not amended or fertilized and the agricultural soils in Peru were amended and fertilized. More recently similar methods including chemical analysis of soils was applied on a more regional scale to Native American agricultural system in the American southwest (Sandor et al., 2007) and more specifically to prehistoric Zuni agricultural systems (Homberg et al., 2005). Note these studies are among only a few that measured any form of nitrogen in geoarchaeological contexts (also see Woods, 1982).

Cavanagh et al. (1988) used HCl-extractable P data to map boundaries of sites in Greece. A positive correlation was found between high pottery sherd densities and high P levels.

The following investigations examine P distributions stratigraphically. Lippi (1988) used stratigraphic data (including artifacts), obtained from cores, and P data, obtained using the field ring test, to map paleosols and activity areas at the Nambillo site in Ecuador. The strata and soil description and P data provided an excellent framework for planning excavations and for making interpretations of land use on the buried landscape surfaces.

Katina (1992) used fractionation to test Eidt's ideas about the correlation of total P with intensity of land use and the use of fraction II/I ratio to determine relative time elapsed since phosphate enrichment. Results of the fractionation were very difficult to interpret because of the land-use palimpsest, but the total P and fraction II/I ratio was used to support soil landscape degradation during the Bronze Age followed by less intensive use during the Middle Ages.

Davidson (1973) used total P (fused with sodium carbonate and measure colorimetrically) from a tell stratigraphic sequence to measure intensity of occupation. P indicates that the (1) intensity of occupation increased up section and (2) the tell sediments have higher P than the local alluvium. He concluded that "phosphorus analysis confirms what might be expected-the tell evolved as a result of occupation and thus the activities of people who occupied the site.... accounts for the growth of the tell" (Davidson 1973, 146).

Bakkevig (1980) claims to get good results from the spot test in part because large numbers of samples can be processed quickly allowing a researcher to obtain data from a large area. The research questions involved correlation of land use with P levels and identifying cattle trails.

Ahler (1973) investigated the distribution of total P (perchloric acid/nitric acid digestion), available P (Brays Strong P test), OM (Walkley-Black), and pH from a stratigraphic sequence at the Rogers Rockshelter in Missouri. Results of the chemical analysis are compared with the distribution of lithic debris and micro-debris (sand-sized material of cultural origin). Ahler's results point out the importance of context for interpreting the chemical data. There is a strong correlation among lithic debris, micro-debris, and total P throughout the sequence and a strong correlation with available P and total P in the lower part of the sequence. The difference between the upper and lower stratum is due to higher sedimentation rates during the accumulation of the lower stratum not allowing pedogenesis to alter the distribution of the available P. It is concluded that total P is more useful for locating intra-site activity areas and available P is more useful for subsurface detection of sites and buried soils especially in strata with pHs similar to those at Rogers shelter.

Conclusions

This brief overview of the uses of carbon, nitrogen, pH, phosphorus, and carbonate analysis in geoarchaeological investigation is far from exhaustive but hopefully illustrated the potential such analyses have for answering archaeological questions. When formulating research questions that involve data generated by chemical analysis, the plan should always have some type of control sampling and an understanding of the physical context of the samples. Control samples are necessary because all of the elements, compounds, and measures covered in this overview occur naturally without any anthropogenic input. So by default the analysis has to be comparative. Context is always important but it is particularly important for chemical analysis because of the multiple physical (stratigraphic/pedogenic), chemical, and anthropogenic transformations that occur during and after human occupations. In many cases the evidences for some types of human activity are all or in part chemical signatures and as such are a valuable tool for targeted geoarchaeological investigations.

Bibliography

Adler, C. J., Haak, W., Donlon, D., and Cooper, A., 2011. Survival and recovery of DNA from ancient teeth and bones. *Journal of Archaeological Science*, **38**(5), 956–964.

Ahler, S. A., 1973. Chemical analysis of deposits at Rogers Rock Shelter, Missouri. *Plains Anthropologist*, **18**, 116–131.

Asouti, E., and Austin, P., 2005. Reconstructing woodland vegetation and its exploitation by past societies, based on the analysis and interpretation of archaeological wood charcoal macroremains. *Environmental Archaeology*, **10**, 1–18.

Bakkevig, S., 1980. Phosphate analysis in archaeology-problems and recent progress. *Norwegian Archaeological Review*, **13**, 73–100.

Barba, L., 2007. Chemical residues in lime-plastered archaeological floors. *Geoarchaeology*, **22**, 439–452.

Barba, L. A., Ortiz, A., Link, K. F., López Lujan, L., and Lazos, L., 1996. The chemical analysis of residues in floors and the reconstruction of ritual activities at the temple Mayor, Mexico. In *Archaeological Chemistry: Organic, Inorganic and Biochemical Analysis*. Washington, DC: Chemical Society of America, pp. 139–156.

Birkeland, P. W., 1984. *Soils and Geomorphology*. New York: Oxford University Press.

Boul, S. W., Hole, F. D., and Mc Cracken, R. J., 1989. *Soil Genesis and Classification*, 3rd edn. Ames, IA: Iowa State University Press.

Braadbaart, F., Poole, I., and van Brussel, A. A., 2009. Preservation potential of charcoal in alkaline environments: an experimental approach and implications for the archaeological record. *Journal of Archaeological Science*, **36**(8), 1672–1679.

Brady, N. C., 1974. *The Nature and Properties of Soil*, 8th edn. New York: MacMillan.

Bremner, J. M., and Mulvaney, C. S., 1982. Nitrogen-total. In Page, A. L. (ed.), *Methods of Soil Analysis. Part 2: Chemical and Biological Properties*. Madison, WI: Soil Science Society of America. Agronomy Monograph, Vol. 9, pp. 595–624.

Cabanes, D., Gadot, Y., Cabanes, M., Finkelstein, I., Weiner, S., Shahack-Gross, R., 2011. Stability of Phytoliths in the Archaeological Record: A Dissolution Study of Modern and Fossil Phytoliths. *Journal of Archaeological Science*, **38**, 2480–2490.

Carr, C., 1982. *Handbook on Soil Resistivity Surveying Interpretation of Data From Earthen Archeological Sites*. Evanston, IL: Center for American Archeology Press.

Cavanagh, W. G., Hirst, S., and Litton, C. D., 1988. Soil phosphate, site boundaries, and change point analysis. *Journal of Field Archaeology*, **15**, 67–83.

Cook, S. F., and Heizer, R. F., 1965. *Studies on the Chemical Analysis of Archaeological Sites*. Berkeley, CA: University of California Press. University of California Publications in Anthropology, Vol. 2.

Courty, M. A., Goldberg, P., and Macphail, R., 1989. *Soils and Micromorphology in Archaeology*. Cambridge: Cambridge University Press. Cambridge Manuals in Archaeology.

Davidson, D. A., 1973. Particle-size and phosphate analysis- evidence for the evolution of a tell. *Archaeometry*, **15**, 143–152.

Dean, W. E. J., 1974. Determination of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss-on-ignition: comparisons with other methods. *Journal of Sedimentary Petrology*, **44**, 242–248.

Dufraisse, A. (ed.), 2006. *Charcoal Analysis: New Analytical Tools and Methods for Archaeology*. British Archaeologcial Report 1483. Oxford, England: Archaeopress.

Dunning, N. P., 1993. Ancient maya anthrosols: soil phosphate testing and land-use. In Timpson, M. E., Foss, J. E., and Morris, M. W. (eds.), *Proceedings of the First International Conference on Pedo-Archaeology*. Knoxville, TN: University of Tennessee Agricultural Experiment Station. Special Publication 93–03, pp. 203–210.

Eidt, R. C., 1973. A rapid chemical field test for archaeological site survey. *American Antiquity*, **38**, 206–210.

Eidt, R. C., 1977. Detection and examination of anthrosols by phosphate analysis. *Science*, **197**, 1327–1333.

Eidt, R. C., 1985. Theoretical and practical considerations in the analysis of anthrosols. In George, R., Jr., and Gifford, J. A. (eds.), *Archaeological Geology*. New Haven, CT: Yale University Press, pp. 155–190.

Entwistle, J. A., Abrahams, P. W., and Dodgshon, R. A., 2000. The geoarchaeological significance and spatial variability of a range of physical and chemical soil properties from a former habitation site, Isle of Skye. *Journal of Archaeological Science*, **27**, 287–303.

Fernández, F. G., Terry, R. E., Inomata, T., and Eberl, M., 2002. An ethnoarchaeological study of chemical residues in the floors and soils of Q'eqchi' Maya houses at Las Pozas, Guatemala. *Geoarchaeology*, **17**(6), 487–519.

Glaser, B., and Woods, W. I. (eds.), 2004. *Amazonian Dark Earths: Explorations in Time and Space*. Berlin: Springer.

Gordon, C. C., and Buikstra, J. E., 1981. Soil pH, bone preservation, and sampling bias at mortuary sites. *American Antiquity*, **46**, 566–571.

Gundlach, H., 1961. Tüpfelmethode auf Phosphat, angewandt in prähistorischer Forschung (als Feldmethode). *Mikrochimica Acta*, **5**, 735–737.

Holliday, V. T., 1994. The "State Factor" approach in geoarchaeology. In Amundson, R., Harden, J., and Singer, M. (eds.), *Factors of Soil Formation: A Fiftieth Anniversary Retrospective.* Madison, WI: Soil Science Society of America. Special Publication Number 33.

Holliday, V. T., 2004a. *Soils in Archaeological Research*. New York: Oxford University Press.

Holliday, V. T., 2004b. Appendix 2: soil phosphorous chemistry, analytical methods, and chronosequences. In Holliday, V. T. (ed.), *Soils in Archaeological Research*. New York: Oxford University Press, pp. 342–362.

Holliday, V. T., Stein, J. K., and Gartner, W. G., 2004c. Appendix 3: variability of soil laboratory procedures and results. In Holliday, V. T. (ed.), *Soils in Archaeological Research*. New York: Oxford University Press, pp. 363–374.

Holliday, V. T., and Gartner, W. G., 2007. Methods of soil P analysis in archaeology. *Journal of Archaeological Science*, **34**(2), 301–333.

Holliday, V. T., and Stein, J. K., 1989. Variability in laboratory procedures and results in geoarchaeology. *Geoarchaeology*, **4**, 347–358.

Homberg, J. A., Sandor, J., and Norton, J. B., 2005. Anthropogenic influences on Zuni agricultural soils. *Geoarchaeology*, **20**, 661–694.

Hooke, R. L. B., Martin-Duque, J. F., and Pedraza, J., 2012. Land transformations by humans: a review. *GSA Today*, **22**, 4–10.

Janitzky, M. J., 1986. Determination of soil pH. In Singer, M. J., and Janitzky, P. (eds.), *Field and Laboratory Procedures Used in a Soil Chronosequence Study*. U.S. Geological Survey Bulletin 1648. Washington, DC: United States Government Printing Office. pp. 19–20

Jenny, H., 1941. *Factors of Soil Formation A System of Quantitative Pedology*. New York: McGraw-Hill.

Katina, L. T., 1992. Phosphate fractionation of soils at Agroal, Portugal. *American Antiquity*, **57**, 495–506.

Kerr, J.P., 1995. Phosphate imprinting within mound a at the Huntsville site. In Collins, M.E., Carter, B. J., Gladfelter, B. G., and Southard, R. J. (eds.), *Pedological Perspectives in Archaeological Research*. Madison, WI: Soil Science Society of America. Special Publication No. 44, pp. 133–149.

Lippi, R. D., 1988. Paleotopography and phosphate analysis of a buried jungle site in Ecuador. *Journal of Field Archaeology*, **15**, 85–97.

Machette, M., 1986. Calcium and magnesium carbonates. In Singer, M. J., and Janitzky, P. (eds.), *Field and Laboratory Procedures Used in a Soil Chronosequence Study*. U.S. Geological Survey Bulletin 1648. Washington, DC: United States Government Printing Office, pp. 30–32.

Marguerie, D., and Hunot, J., 2007. Charcoal analysis and dendrochronology: data from archaeological sites in Northwestern France. *Journal of Archaeological Science*, **34**, 1417–1433.

McCann, J. M., Woods, W. I., and Meyer, D. W., 2001. Organic matter and anthrosols in Amazonia: interpreting the Amerindian legacy. In Ball, B., Rees, R. M., Watson, C., and Campbel, C. (eds.), *Sustainable Management of Soil Organic Matter*. Wallingford, CT: CAB, International, pp. 180–189.

McLean, E.O., 1982. Soil pH and lime requirement. In Page, A.L., (ed.), *Methods of Soil Analysis. Part 2: Chemical and Biological Properties, Soil Science Society of America*. Madison, WI: Soil Science Society of America. Agronomy Monograph No. 9, pp. 199–224.

Meixner, R., 1986a. Total phosphorous (extraction). In Singer, M. J., and Janitzky, P. (eds.), *Field and Laboratory Procedures Used in a Soil Chronosequence Study*. U.S. Geological Survey Bulletin 1648. Washington, DC: United States Government Printing Office, p. 44.

Meixner, R., 1986b. Phosphorous fractionation (extraction). In Singer, M. J., and Janitzky, P. (eds.), *Field and Laboratory Procedures Used in a Soil Chronosequence Study*. U.S. Geological Survey Bulletin 1648. Washington, DC: United States Government Printing Office, p. 44.

Meixner, R., 1986c. Phosphorous analysis. In Singer, M. J., and Janitzky, P. (eds.), *Field and Laboratory Procedures Used in a Soil Chronosequence Study*, Washington, DC: United States Government Printing Office, pp. 45–46.

Middleton, W., D., Barba, L., Pecci, A., Burton, J. H., Ortiz, A., Salvini, L., and Suarez, R. R., 2010. The study of archaeologcial floors: methodological proposal for the analysis of anthropogenic residues by spot tests, ICP-OES, and GC-MS. *Journal of Archaeological Method and Theory*, **17**, 183–208.

Moskal-del Hoyo, M., Wachowiak, M., and Blanchette, R. A., 2010. Preservation of fungi in archaeological charcoal. *Journal of Archaeological Science*, **37**, 2106–2116.

Nelson, R. E., 1982. Carbonate and gypsum. In Page, A. L., (ed.), *Methods of Soil Analysis. Part 2: Chemical and Biological Properties, Soil Science Society of America*. Madison, WI: Soil Science Society of America. Agronomy Monograph No. 9, pp. 181–197.

Nelson, D. W., and Sommers, L. E., 1982. Total carbon, organic carbon, and organic matter. In Page, A. L., (ed.), *Methods of Soil Analysis. Part 2: Chemical and Biological Properties, Soil Science Society of America*. Madison, WI: Soil Science Society of America. Agronomy Monograph No. 9, pp. 539–579.

Nielsen-Marsh, C. M., Smith, C. I., Jans, M. M. E., Nord, A., Kars, H., and Collins, M. J., 2007. Bone diagenesis in the European Holocene II: taphonomic and environmental considerations. *Journal of Archaeological Science*, **34**(9), 1523–1531.

Olsen, R. L., and L. E. Sommers. 1982. Phosphorous. In Page, A. L. (ed.), *Methods of Soil Analysis. Part 2: Chemical and Biological Properties.* Madison, WI: Soil Science Society of America. Agronomy Monograph No. 9, pp. 403–430.

Parnell, J. J., Terry, R. E., and Golden, C., 2001. Using in-field phosphate testing to rapidly identify middens at Piedras Negras, Guatemala. *Geoarchaeology*, **16**(8), 855–873.

Parnell, J. J., Terry, R. E., and Nelson, Z., 2002. Soil chemical analysis applied as an interpretive tool for ancient human activities in Piedras Negras, Guatemala. *Journal of Archaeological Science*, **29**, 379–404.

Pate, F. D., and Hutton, J. T., 1988. The use of soil chemistry data to address post-mortem diagenesis in bone mineral. *Journal of Archaeological Science*, **15**(6), 729–739.

Piperno, D., 2006. *Phytoliths a Comprehensive Guide for Archaeologists and Paleoecologists*. Lanham, MD: AltaMira Press.

Proudfoot, B., 1976. The analysis and interpretation of soil phosphorous in archaeological contexts. In Davidson, D. A., and Shackley, M. L. (eds.), *Geoarchaeology.* Boulder, CO: Westview Press, pp. 94–113.

Prychid, C. J., Jabaily, R. S., and Rudall, P. J., 2008. Cellular ultrastructure and crystal development in *Amorphophallus* (Araceae). *Annals of Botany*, **101**, 983–995.

Roberts, T. L., Stewart, J. W. B., and Bettany, J. R., 1985. Influence of topography on the distribution of organic and inorganic soil phosphorous across a narrow environmental gradient. *Canadian Journal of Soil Science*, **65**, 651–665.

Roos, C. I., and Nolan, K. C., 2012. Phosphates, plowzones, and plazas: a minimally invasive approach to settlement structure of plowed village sites. *Journal of Archaeological Science*, **39**, 23–32.

Sandor, J. A., 1992. Long-term effects of prehistoric agriculture on soils: examples from New Mexico and Peru. In Holliday, V. T. (ed.), *Soils in Archaeology Landscape Evolution and Human Occupation*. Washington DC: Smithsonian Institution Press, pp. 217–245.

Sandor, J. A., Norton, J. B., Homburg, J. A., Muenchrath, D. A., White, C. S., Williams, S. E., Havener, C. I., and Stahl, P. D., 2007. Biogeochemical studies of a Native American runoff agroecosystem. *Geoarchaeology*, **22**(3), 359–386.

Schiegl, S., Goldberg, P., Bar-Yosef, O., and Weiner, S., 1996. Ash deposits in hayonim and kebara caves, Israel: microscopic, microscopic, and mineralogic observations, and their archaeological implications. *Journal of Archaeological Science*, **23**, 763–781.

Schuldenrein, J., 1995. Geochemistry, phosphate fractionation, and the detection of activity areas at Prehistoric North American Sites. In Collins, M.E., Carter, B. J., Gladfelter, B. G., and Southard, R. J. (eds.), *Pedological Perspectives in Archaeological Research*. Madison, WI: Soil Science Society of America. Special Publication No. 44, pp. 107–132.

Schuman, G. E., Stanley, M. A., and Knudson, D., 1973. Automated total nitrogen analysis of soil and plant samples. *Soil Science Society of America Journal*, **37**, 480–481.

Shacklette, H.T., and Boerngen, J. G., 1984. *Element Concentrations in Soils and Other Surficial Materials of the Conterminous U. S.* United States Geological Survey Professional Paper 1270. Washington, DC: United States Government Printing Office.

Sheppard, P. J., and Pavlish, L. A., 1992. Weathering of archaeological cherts: a case study from the Solomon Islands. *Geoarchaeology*, **7**, 41–53.

Singer, M. J., and Janitzky, P., 1986. *Field and Laboratory Procedures Used in a Soil Chronosequence Study.* U.S. Geological Survey Bulletin 1648. Washington, DC: United States Government Printing Office.

Skinner, S., 1986. Phosphorous as an anthrosol indicator. *Midcontinental Journal of Archaeology*, **11**, 51–78.

Soil Science Society of America, 1997. *Glossary of Soil Science Terms*. Revised Edition. Madison, WI: Soil Science Society of America.

Sposito, G., 1989. *The Chemistry of Soils*. New York: Oxford University Press.

Stein, J. K., 1992. Organic matter in archaeological contexts. In Holliday, V. T. (ed.), *Soils in Archaeology Landscape Evolution and Human Occupation*. Washington DC: Smithsonian Institution Press, pp. 193–216.

Stevenson, F. J., and Coles, M. A., 1999. *Cycles of Soil: Carbon, Nitrogen, Phosphorous, Sulfur, and Micronutrients*. New York: Wiley.

Terry, R. E., Nelson, S. D., Carr, J., Parnell, J., Hardin, P. J., Jackson, M. W., and Houston, S. D., 2000. Quantitative phosphorus measurement: a field test procedure for archaeological site analysis at Piedras Negras, Guatemala. *Geoarchaeology*, **15**(2), 151–166.

Terry, R. E., Fernández, F. G., Parnell, J., and Inomata, T., 2004. The story in the floors: chemical signatures of ancient and modern Maya activities at Aguateca, Guatemala. *Journal of Archaeological Science*, **31**(9), 1237–1250.

Thery-Parisot, I., Chabal, L., and Chrzavzez, J., 2010. Anthracology and taphonomy, from wood gathering to charcoal analysis. A review of the taphonomic processes modifying charcoal assemblages, in archaeological context. *Paleogeography, Paleoclimatology, Paleoecology*, **291**, 142–153.

Thomas, R. L., Sheard, R. W., and Moyer, J. R., 1967. Comparison of conventional and automated procedures for nitrogen, phosphorous, and potassium analysis of plant material using a single digestion. *Agronomy Journal*, **59**, 240–243.

Tiessen, H., Stewart, J. W. B., and Cole, C. V., 1984. Pathways of phosphorous transformations in soils of differing pedogenesis. *Soil Science Society of America Journal*, **48**, 853–858.

Tylecote, R. F., 1979. The effect of soil conditions on the long-term corrosion of buried Tin-Bronzes and Copper. *Journal of Archaeological Science*, **6**(4), 345–368.

Walker, T. W., and Syers, J. K., 1976. The fate of phosphorous during pedogenesis. *Geoderma*, **15**, 1–19.

Weiner, S., Goldberg, P., and Bar-Yosef, O., 2002. Three-dimensional distribution of minerals in the sediments of Hayonim Cave, Israel: diagenetic processes and archaeological

implications. *Journal of Archaeological Science*, **29**, 1289–1308.
Wells, E. C., and Terry, R. E., 2007. Introduction. *Geoarchaeology*, **22**(4), 387–390.
Wells, E. C., Terry, R. E., Parnell, J. J., Hardin, P. J., Jackson, M. W., and Houston, S. D., 2000. Chemical analyses of ancient anthrosols in residential areas at Piedras Negras, Guatemala. *Journal of Archaeological Science*, **27**, 449–462.
White, E. M., 1978. Cautionary note on phosphate data interpretation for archaeology. *American Antiquity*, **43**, 507–508.
Woods, W. I., 1975. *The Analysis of Abandoned Settlements by a New Phosphate Field Test Method*. Norfolk, VA: Chesopiean Archaeological Society.
Woods, W. I., 1982. Analysis of soils from the carrier mills archaeological district. In Jefferies, R. W., and Butler, B. M., (eds.), *The Carrier Mills Archaeological Project: Human Adaptations in the Saline Valley, Illinois*. Carbondale, IL: Center for Archaeological Investigations, Southern Illinois University, Research Paper No. 33, pp. 1381–1407.

ANTHROSOLS

Vance T. Holliday
Anthropology and Departments Geosciences,
University of Arizona, Tucson, AZ, USA

Definition

Soils or sediments exhibiting significant chemical inputs as well as obvious physical changes resulting from human activity are called anthrosols.

Introduction

In the FAO (2006) soil classification system, anthrosol is one of the major soil groupings for a broad array of soils "in which human activities have resulted in profound modification or burial of the original soil horizons" (p. 61). Anthrosols vary widely in their physical and chemical characteristics, and few traits are universal. There are several characteristics that are common or that serve as clues to the presence of significant modification due to human activity. The most obvious is the presence of archaeological debris within the soil, in particular organic detritus such as bone and charcoal in a surface horizon, i.e., they tend to be associated with middens. Other physical features, typically applying to surface horizons, include: abrupt, smooth boundaries between horizons or layers; abrupt, laterally discontinuous layers; and dark matrix colors (low value and chroma in the Munsell color system) extending to greater-than-expected depths for natural soils in the area (following Collins and Shapiro, 1987). The greater-than-expected depth is usually due to artificial upbuilding. Chemical signatures include higher-than-expected values of organic matter relative to natural soils and, in particular, phosphate (see below). Anthrosols may also have been subjected to some form of pedogenic alteration albeit relatively minor pedogenesis in many instances.

Types of anthrosols

Anthrosols can include a wide array of soils, but three types have been described at some length: Plaggen, Dark Earths, and Terra Preta. Various other kinds of middens may also qualify as anthrosols.

Plaggen soils are most common on the sandy landscapes of the Netherlands, Germany, and Belgium, but similar soils are reported from other parts of northern Europe and Great Britain, Crete, Peru, and New Zealand (Kalinina et al., 2009; Van Mourik et al., 2011). They developed in the Middle Ages, probably around the tenth century (Pape, 1970; Heidinga, 1988; van de Westeringh, 1988). Manure was the preferred fertilizer, so in order to gather it, the floors of stables were strewn with forest litter, heather turves (slabs of heather cut from the ground), or grass sod to absorb the droppings from sheep and cattle. The mixture of manure, bedding, and mineral matter was then hauled out and strewn on fields. The mineral material brought in with the bedding sometimes provided additional nutrients. The mixture of manure, bedding, and mineral matter increased water-holding capacity and also deepened the plow zone, thus minimizing crop failure.

The *Dark Earth* is common in cities throughout much of Europe ("Urbic Anthrosols" of FAO, 2006). "Dark Earth" is a term applied to dark-colored, seemingly homogeneous urban deposits. In many ways, they can be considered anthropogenic sediments rather than soil, but they have undergone surface weathering and are typically considered a soil. In Britain, these soils are linked to late- or post-Roman, Saxon, Viking, Medieval, and perhaps post-Medieval occupation. General characteristics of Dark Earths include "an exceedingly uniform color" of dark grayish brown (with Munsell color coding 10YR 4/2) dry, to very dark gray (10YR 3/11) moist, mildly alkaline pH, some $CaCO_3$ (<10 %), 1–2 % organic carbon, some phosphate, and abundant midden debris (Courty et al., 1989, 262).

The *terra preta do Índio* ("black earth of the Indian") or simply *Terra Preta* soil of the Amazon Basin is a well-drained soil characterized by the presence of a thick black, or dark gray, topsoil which contains artifacts (Figure 1). They are found on upland areas adjacent to waterways along older terraces and also on interior uplands (Woods, 1995; Woods and McCann, 1999; Schmidt et al., 2014). In all settings, the dark colors of the Terra Preta contrast strongly with underlying subsoils which are red to yellow Ultisols, Oxisols, Spodosols, and eutrophic Oxisols (Sombroek, 1966; Smith, 1980; Lima et al., 2002). Terra Preta vary considerably in their distribution, morphology, and genesis. The classic black Terra Preta and associated midden debris represent household or near-household trash dumps (e.g., Birk et al., 2011; Schmidt, 2014), but the more ubiquitous dark brown *Terra Mulata*, largely devoid of artifacts or other obvious human debris, may

Anthrosols, Figure 1 A Terra Preta soil of the Brazilian Amazon containing ceramic debris (Photo by William Woods).

represent agricultural soils modified by repeated mulching and frequent burning. This model of soil genesis has some important archaeological implications. It suggests long-standing habitation sustained by permanent gardens and fields. It also contradicts long-held models of settlement in the Amazon based on presumed agricultural limitations of upland and interior soils (see Denevan, 2001).

More broadly, the most widespread activity leading to development of anthrosols is agriculture (see entry on Soils, Agricultural in this volume). The development of agriculture probably has had more pervasive physical and chemical effects on soils than any other activity by preindustrial societies (Goudie, 2000, 29). Agriculture has imposed host of far-reaching effects on the landscape and on soils. The original plant cover can be partially or completely removed, leaving the ground bare for at least some part of the year and subject to erosion by water or wind. Cultivation loosens the soil and the hooves of domesticated animals can further loosen or compact it. Devegetation alters soil moisture and can affect groundwater. Plowing, excavation of irrigation ditches, and construction of terraced fields all physically disturb soils as well. Devegetation, new kinds of plant residues (from burning and cropping), and additions of fertilizer can all alter soil chemistry. Changes in groundwater conditions can drastically affect the soil forming environment. An elevated water table as well as irrigation also induces salinization if salts are present.

The unique morphological (macro- and micro-) and chemical characteristics of soils provide an excellent backdrop against which agricultural activities may be identified (Limbrey, 1975; Courty et al., 1989; Holliday, 2004). The physical signatures of agriculture in soils are related to the disruption of the lateral continuity of and vertical gradations between soil horizons. These disruptions result largely from plowing and the cutting of ditches and furrows. Probably the most obvious initial effect of farming is mixing of the upper solum by plowing. This process is widely recognized today in the identification of the "Ap" plowzone horizon.

At microscopic and chemical scales, impacts on soils due to human activity are generally much more subtle than physical impacts and usually require laboratory analyses for identification. Microscopically, the effects of agriculture include evidence for rapid infiltration of coarse-grained illuvial coatings from downward percolation of solutes or fine particles due to deforestation, and poorly-sorted mineral coatings and infillings of charcoal and SOM (soil organic matter; see below) due to farming.

Chemical impacts on soils come from human refuse and waste, burials, the products of animal husbandry in barns, pens, and on livestock paths, or intentional enrichment from soil fertilizer. With the advent of metallurgy and later industrialization, a much broader spectrum of chemicals and chemical compounds was added to the soil, such as heavy metals and hydrocarbons. The most common chemical elements added to soils by human activity are carbon, nitrogen, phosphorus, and calcium, with lesser amounts of potassium, magnesium, sulfur, copper, and zinc. The most common chemical compound added to soils by humans in agricultural and preagricultural societies and that is also easily recognizable in the field is soil organic matter (SOM). Human activity, largely through discard of organic waste (either in middens or as fertilizer), can add significant amounts of organic matter to the soil surface. Further, additional SOM can be produced and added to the soil by stimulation of soil biota and above-ground biomass subsequent to human activity due to more favorable nutrient conditions often associated with anthropogenic changes. These are notable characteristics of the anthrosols described below.

Anthropogenic additions of carbon, nitrogen, phosphorus, calcium, potassium, magnesium, and sulfur in theory can be used as indicators of past human activity. Most of these elements are removed from soil more or less readily by leaching, oxidation, reduction, or plant uptake, however (Eidt, 1977; Carr, 1982, 127–131), and the nature and rates of these losses from the soil are determined by local biological and pedological processes. Phosphorus in its common form as phosphate, however, is stable and generally immobile in soils and is thus a sensitive and persistent indicator of human activity. Among the elements left in the soil by humans, only P leaves a prolonged signature of its human origins because natural and anthropogenic P tend to be strongly fixed in soils. The sources of anthropogenic phosphorus include (1) human and animal waste; (2) refuse derived from bone, meat, fish, and plants; (3) burials; and (4) manure used as fertilizer (Provan, 1971; Proudfoot, 1976; Eidt, 1984, 29–30; Bethell and Máté, 1989). When people add P to the soil as organic products or inorganic compounds, the P quickly bonds with Fe, Al, or Ca ions (depending on local chemical conditions, particularly pH) to form relatively stable chemical compounds of inorganic phosphate minerals (Proudfoot, 1976; Bethell and Máté, 1989; Holliday and Gartner, 2007). In most soils, removal of these compounds cannot be stimulated by normal oxidation, reduction, or leaching processes, as is true of other elements (Proudfoot, 1976; Eidt, 1977, 1984, 1985). When humans add P to the soil, therefore, it accumulates at the site of deposition. With prolonged occupation, the accumulation of anthropogenic P can become quite large (by orders of magnitude) in comparison to the content of natural P in the soil. Other elements are cycled much more rapidly, assisted by microorganisms and plants in their cycling through the ecosystem, so the record of their association with people is lost.

Another factor which makes P suitable for geoarchaeological study is that anthropogenic P can exist in the pH range of most soils. Under acidic conditions, P combines with iron and aluminum, whereas under basic conditions, P combines with calcium. Consequently, soil P analysis can be used successfully in a wide variety of archaeological contexts. Indeed, where there is little or no surface evidence of human occupation, soil P analysis may be an appropriate tool for detecting traces of human activity and for determining the particular form and function associated with that presence.

The proportional relationships of certain ions have also been investigated archaeologically. Soil pH, which is an expression of the proportion of H^+ ions (or protons) to OH^- (hydroxyl) ions, has some sensitivity to anthropogenic inputs. The concentration of cations (positively charged ions) in the soil strongly influences pH. Prolonged or more intense occupations tend to release more cations to the soil, and therefore, pH tends to be higher within deposits laid down under longer, denser, or more intensely occupied sites (Carr, 1982, 112).

Bibliography

Bethell, P., and Máté, I., 1989. The use of soil phosphate analysis in archaeology: a critique. In Henderson, J. (ed.), *Scientific Analysis in Archaeology and Its Interpretation*. Los Angeles: UCLA Institute of Archaeology. UCLA Institute of Archaeology, Archaeological Research Tools 5, pp. 1–29.

Birk, J. J., Teixeira, W. G., Neves, E. G., and Glaser, B., 2011. Faeces deposition on Amazonian Anthrosols as assessed from 5β-stanols. *Journal of Archaeological Science*, **38**(6), 1209–1220.

Carr, C., 1982. *Handbook on Soil Resistivity Surveying: Interpretation of Data from Earthen Archeological Sites*. Evanston: Center for American Archaeology Press.

Collins, M. E., and Shapiro, G., 1987. Comparisons of human-influenced and natural soils at the San Luis archaeological site, Florida. *Soil Science Society of America Journal*, **51**(1), 171–176.

Courty, M. A., Goldberg, P., and Macphail, R. I., 1989. *Soils and Micromorphology in Archaeology*. Cambridge: Cambridge University Press.

Denevan, W. M., 2001. *Cultivated Landscapes of Native Amazonia and the Andes*. Oxford: Oxford University Press.

Eidt, R. C., 1977. Detection and examination of anthrosols by phosphate analysis. *Science*, **197**(4311), 1327–1333.

Eidt, R. C., 1984. *Advances in Abandoned Settlement Analysis: Application to Prehistoric Anthrosols in Colombia, South America*. Milwaukee: University of Wisconsin-Milwaukee, Center for Latin America.

Eidt, R. C., 1985. Theoretical and practical considerations in the analysis of anthrosols. In Rapp, G. R., and Gifford, J. A. (eds.), *Archaeological Geology*. New Haven: Yale University Press, pp. 155–190.

FAO, 2006. *World Reference Base for Soil Resources 2006: A Framework for International Classification, Correlation and Communication*. Rome: Food and Agriculture Organization of the United Nations. World Soil Resources Report 103.

Goudie, A. S., 2000. *The Human Impact on the Natural Environment*, 5th edn. Cambridge, MA: MIT Press.

Heidinga, H. A., 1988. Climate and plaggen soils. In Groennmann-van Waateringe, W., and Robinson, M. (eds.), *Man-Made Soils*. Oxford: British Archaeological Reports. British Archaeological Reports, International Series 410, pp. 21–33.

Holliday, V. T., 2004. *Soils in Archaeological Research*. Oxford: Oxford University Press.

Holliday, V. T., and Gartner, W. G., 2007. Methods of soil P analysis in archaeology. *Journal of Archaeological Science*, **34**(2), 301–333.

Kalinina, O., Chertov, O., Nadporozhskaya, M., and Giani, L., 2009. Properties of soil organic matter of Plaggic Anthrosols from Northwest Germany, Northwest and North Russia. *Archives of Agronomy and Soil Science*, **55**(5), 477–492.

Lima, H. N., Schaefer, C. E. R., Mello, J. W. V., Gilkes, R. J., and Ker, J. C., 2002. Pedogenesis and pre-Colombian land use of "Terra Preta Anthrosols" ("Indian black earth") of western Amazonia. *Geoderma*, **110**(1–2), 1–17.

Limbrey, S., 1975. *Soil Science in Archaeology*. London: Academic Press.

Pape, J. C., 1970. Plaggen soils in The Netherlands. *Geoderma*, **4**(3), 229–255.

Proudfoot, B., 1976. The analysis and interpretation of soil phosphorus in archaeological contexts. In Davidson, D. A., and Shackley, M. L. (eds.), *Geoarchaeology: Earth Science and the Past*. Boulder: Westview Press, pp. 93–113.

Provan, D. M. J., 1971. Soil phosphate analysis as a tool in archaeology. *Norwegian Archaeological Review*, **4**(1), 37–50.

Schmidt, M. J., 2014. In Rostain, S. (ed.), *Antes de Orellana. Actas del 3er Encuentro Internacional de Arqueología Amazónica*. Lima: Instituto Francés de Estudios Andinos, pp. 331–337. 545–546.

Schmidt, M. J., Py-Daniel, A. R., Moraes, C. d. P., Valle, R. B. M., Caromano, C. F., Texeira, W. G., Barbosa, C. A., Fonseca, J. A., Magalhães, M. P., Silva do Carmo Santos, D., da Silva e Silva, R., Guapindaia, V. L., Moraes, B., Lima, H. P., Neves, E. G., and Heckenberger, M. J., 2014. Dark earths and the human built landscape in Amazonia: a widespread pattern of anthrosol formation. *Journal of Archaeological Science*, **42**, 152–165.

Smith, N. J. H., 1980. Anthrosols and human carrying capacity in Amazonia. *Annals of the Association of American Geographers*, **70**(4), 553–566.

Sombroek, W. G., 1966. *Amazon Soils: A Reconnaissance of the Soils of the Brazilian Amazon Region*. Wageningens: Centre for Agricultural Publications and Documentation.

Van de Westeringh, W., 1988. Man-made soils in the Netherlands, especially in sandy areas ("plaggen soils"). In Groennmann-van Waateringe, W., and Robinson, M. (eds.), *Man-Made Soils*. Oxford: British Archaeological Reports. British Archaeological Reports, International Series 410, pp. 5–19.

Van Mourik, J. M., Slotboom, R. T., and Wallinga, J., 2011. Chronology of plaggic deposits; palynology, radiocarbon and optically stimulated luminescence dating of the Posteles (NE-Netherlands). *Catena*, **84**(1–2), 54–60.

Woods, W. I., 1995. Comments on the black earths of Amazonia. In Schoolmaster, F. A. (ed.), *Papers and Proceedings of Applied Geography Conferences*, Vol. **18**, pp. 159–165.
Woods, W. I., and McCann, J. M., 1999. The anthropogenic origin and persistence of Amazonian dark earths. *The Yearbook of the Conference of Latin American Geographers*, **25**, 7–14.

Cross-references

Analysis of Carbon, Nitrogen, pH, Phosphorus, and Carbonates as Tools in Geoarchaeological Research
Dumps and Landfill
Shell Middens
Soils, Agricultural

^{40}AR/^{39}AR AND K–AR GEOCHRONOLOGY

Leah E. Morgan
Scottish Universities Environmental Research Centre, East Kilbride, UK

Synonyms

Ar–Ar dating; Argon–argon dating; K–Ar dating

Definition

K–Ar geochronology. A geochronometer (geologic dating method) used to date potassium-bearing rocks, based on the decay of parent isotope ^{40}K to daughter isotope ^{40}Ar.

^{40}Ar/^{39}Ar geochronology. A variant of the K–Ar geochronometer, where ^{39}Ar is measured as a proxy for the parent isotope ^{40}K.

Introduction

The K–Ar method and its derivative, the ^{40}Ar/^{39}Ar method, are based on the radioactive decay of ^{40}K to the noble gas ^{40}Ar (sometimes symbolically indicated as ^{40}Ar*, or radiogenic Ar). Potassium (K) is a major element in the Earth's crust and is abundant in many rocks and minerals. It possesses two stable isotopes: ^{39}K (93 %) and ^{41}K (7 %). After some early indications that a radioactive isotope of potassium of mass 40 might exist (for details see McDougall and Harrison, 1999, and references therein), it was definitively identified by Nier (1935). It was not until later that rocks enriched in ^{40}Ar were identified and the first K–Ar ages produced on K-bearing feldspar and salt minerals (Aldrich and Nier, 1948). Evernden and Curtis (1965) presented the first application of the K–Ar method to constrain ages of paleoanthropological localities by dating rock layers, such as tephra and basalt at Olduvai Gorge, that lie stratigraphically above or below a significant archaeological deposit. Since then, K–Ar and ^{40}Ar/^{39}Ar have been used to constrain the age of numerous paleoanthropological localities, including archaeological events as recent as the AD 79 eruption of Vesuvius that buried the Roman towns of Pompeii and Herculaneum (Renne et al., 1997).

Problematic issues with the K–Ar method (see below for details) were resolved with the introduction of neutron irradiation of samples prior to analysis (Merrihue and Turner, 1966). Irradiation converts some ^{39}K to ^{39}Ar, allowing for determination of parent and daughter isotopes using single samples and ultimately permitting single-crystal analyses. Early applications of the ^{40}Ar/^{39}Ar method included efforts to constrain the age of the KBS Tuff in Koobi Fora, Kenya (Fitch and Miller, 1970; Fitch et al., 1974; Fitch et al., 1976; McDougall et al., 1980; McDougall, 1981).

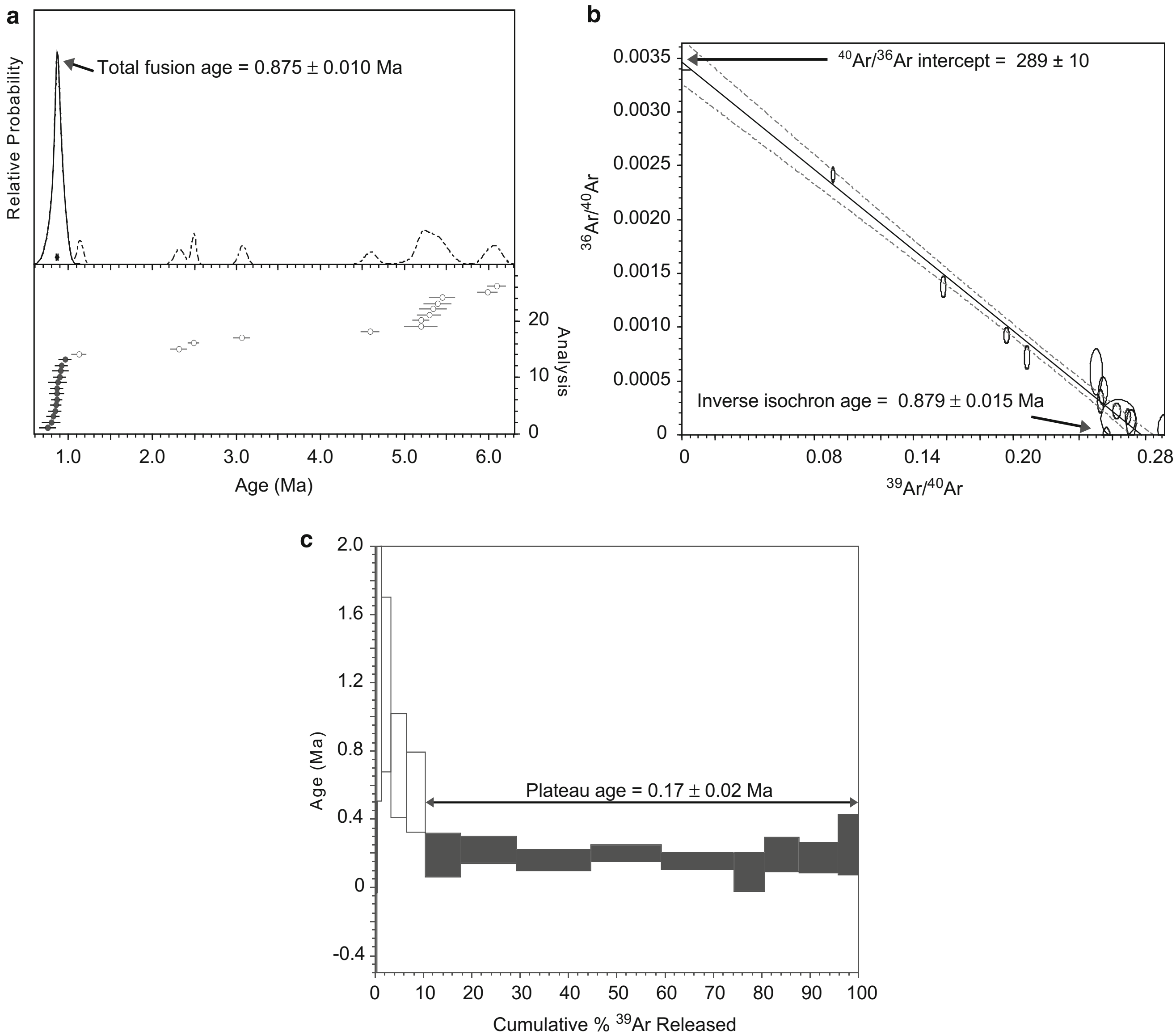
Today, ^{40}Ar/^{39}Ar geochronology has largely superseded K–Ar and is applied to volcanic units at archaeological and paleontological sites globally. The method continues to play a key role in establishing timescales of human biological and behavioral evolution in regions with volcanic deposits.

Principles of K–Ar and ^{40}Ar/^{39}Ar geochronology

The K–Ar and related ^{40}Ar/^{39}Ar methods are based on the constant rate of decay of ^{40}K to ^{40}Ar. A common measure of decay is the half-life, during which time half of the ^{40}K atoms in a given system will decay. The ^{40}K decay is a branched one, where about 90 % of atoms decay to ^{40}Ca, while about 10 % of atoms transform into ^{40}Ar. Application of these systems to archaeological environments is based on their ability to record the age of eruption for in situ volcanic rocks, which have been shown to be related in some way to archaeological remains, e.g., as a capping or underlying layer. Thus, the ages of crystallization for newly formed rocks or minerals are determined and used to bracket the dates of deposition for archaeological or paleoanthropological sites that are stratigraphically related.

The process often begins in a magma chamber within the Earth's crust, where K-bearing crystals of minerals such as feldspars, biotite, and hornblende form prior to eruption. At the high temperatures present in magma chambers, any ^{40}Ar created by ^{40}K decay within a crystal naturally diffuses out of the crystal. Upon eruption and subsequent cooling, argon diffusion is slowed so that any ^{40}Ar created after the eruption is quantitatively retained within the crystal, thereby starting a radioactive "clock." By measuring the ratio of the "daughter" isotope (^{40}Ar) to the "parent" isotope (^{40}K), combined with values of the half-life for the branched decay of ^{40}K, one can calculate the time that has passed since cooling. In the K–Ar method, assays must be conducted on two aliquots of the same sample, i.e., two crystals (or groups of crystals) from the same source: one to determine the amount of ^{40}K and another to determine the amount of ^{40}Ar.

The ^{40}Ar/^{39}Ar method has ameliorated a number of issues involved with application of the K–Ar method, including that it allows for the measurement of K and Ar on a single-sample aliquot. This ^{40}Ar/^{39}Ar variant relies on neutron irradiation of samples prior to analysis to



^{40}Ar/^{39}Ar and K–Ar Geochronology, Figure 1 Examples of ^{40}Ar/^{39}Ar data presentation. (**a**) Relative probability diagram for total fusion data from single crystal analyses. The youngest population, which is interpreted here to represent eruption age, is shown in black; xenocrystic contamination by older grains shown in gray (analytical data) and dashed lines (probability). Reproduced with permission from Morgan et al. (2012). (**b**) Same data as (**a**) graphed onto an inverse isochron diagram. The mixing line fit to the data indicates a trapped ^{40}Ar/^{36}Ar component nearly indistinguishable from the atmospheric value of 298.56, and a radiogenic component with an age of ca. 879 ka. Reproduced with permission from Morgan et al. (2012). (**c**) Age spectrum from incremental heating data. Data from argon released during consecutive heating steps are shown from left to right. Note that consistent ages are identified over the last nine steps represented by the horizontal line; the weighted mean of these steps is presented as the plateau age (ca. 170 ka), which is read on the vertical axis. Earlier steps are inconsistent and omitted. Reproduced with permission from Morgan et al. (2009).

convert some fraction of the ^{39}K present in the sample to ^{39}Ar and therefore permit the measurement of ^{39}Ar as a proxy for the parent isotope ^{40}K. This is possible by using a natural value for the global ^{40}K/^{39}K ratio (for purposes of most applications, this value is reasonably assumed to be constant).

A major advantage of the ^{40}Ar/^{39}Ar system is that it allows for all required measurements to be made on a single-sample aliquot. Thus, analysis of single crystals becomes possible, permitting the identification of contamination from older, embedded crystals (or xenocrysts) that can be masked when using multigrain aliquots (Figure 1a).

In order to provide reliable ages, samples for $^{40}Ar/^{39}Ar$ analysis must be coirradiated with standards of a known age to determine the precise neutron flux of the reactor during irradiation. These standards may have been previously dated via K–Ar analyses (Lanphere and Dalrymple, 1966; McDougall and Roksandic, 1974; McDougall and Wellman, 2011) or based on intercalibration with other systems, such as the astronomical timescale (Kuiper et al., 2008) or the U–Pb geochronometer (Renne et al., 2010; Renne et al., 2011). The standard ages and decay constant values used to calculate $^{40}Ar/^{39}Ar$ ages have changed over time, typically as more precise and accurate values are determined. Understanding and comparing $^{40}Ar/^{39}Ar$ ages thus requires knowledge of the values used for their calculation.

When single grains are sufficiently large and/or old (thereby providing greater amounts of radiogenic ^{40}Ar), the $^{40}Ar/^{39}Ar$ system can be further exploited by incrementally heating samples (rather than releasing all gas in a single, "total fusion" heating step). The "age spectrum" (Figure 1c) obtained by an incremental heating analysis can be used to identify problematic samples, assess the homogeneity of argon in crystals, and understand the thermal history of a sample.

Finally, when using the K–Ar method, one must make the assumption that argon trapped in the crystal upon cooling had an $^{40}Ar/^{36}Ar$ value equivalent to that of the present atmosphere. Most atmospheric argon is ^{40}Ar (99.6 %) and was produced by the decay of ^{40}K, while argon in the solar system and beyond is largely ^{36}Ar (85 %), which is rare on Earth and forms a ratio of $^{40}Ar/^{36}Ar$ in Earth's atmosphere of 298.56:1 (Lee et al., 2006). This assumption can be tested using the $^{40}Ar/^{39}Ar$ method by viewing either total fusion or incremental heating data on an inverse isochron diagram (Figure 1b). This diagram shows the mixing between the trapped component $^{36}Ar/^{40}Ar$ (Y-intercept) and the radiogenic component $^{39}Ar/^{40}Ar$ (X-intercept). Deviations from an atmospheric trapped component, which are particularly important for young samples, can be identified and rectified.

Sample materials

In archaeological settings, K–Ar and $^{40}Ar/^{39}Ar$ geochronology are often applied to various kinds of lavas and consolidated volcanic ashes, or tuffs. Within these materials, frequently analyzed potassium-bearing minerals include feldspars (particularly K-rich sanidine but also anorthoclase and plagioclase), biotite, and hornblende. Because of their young age, samples relevant to archaeological sites require higher potassium concentrations to obtain precise ages, so the utility of minerals with less K, such as plagioclase feldspars, is limited. For all samples, impurities such as fluid inclusions and alteration products should be avoided. For single-crystal work on young samples, desired grains are typically >250 μm. Although recent analytical improvements and optimum samples allow for analysis of grains as small as 50 μm, smaller grain sizes produce unreliable results due to nuclear effects during irradiation (Paine et al., 2006; Jourdan et al., 2007).

Analyses of lava flow samples can be conducted on mineral separates (e.g., one of the K-bearing minerals listed above), groundmass (microcrystalline matrix), or whole rock. Groundmass analyses require the separation of phenocrysts from a crushed sample, while in the case of whole rock, sample fragments are sufficient. Although care must be taken, some volcanic glasses such as obsidian can be a viable material for $^{40}Ar/^{39}Ar$ analyses, but glass shards from volcanic ashes have been shown to yield unreliable results that are difficult to recognize as inaccurate (Morgan et al., 2009).

The method can be applied to rocks as old as the Earth and, depending on their K content and required precision, as young as 1 ka. For example, basalts as young as 3 ka have been dated with precisions of 1 ka (1σ, here and throughout) (Hicks et al., 2012). Similarly, K-rich feldspars as young as the eruption of Vesuvius that destroyed Pompeii in AD 79 have been dated (accurately according to historical records) to 1.925 ± 0.047 ka (Renne et al., 1997). Precision typically degrades as signal size decreases (along with K content, age, and grain size), but it is important to distinguish analytical precision from accuracy, especially when comparing ages from different chronometers. Calibrations of standard ages and decay constants can result in total (analytical + systematic) uncertainties as low as <0.2 % at ca. 1 Ma (Renne et al., 2010; Renne et al., 2011), but perhaps more typical are uncertainties at the 1–2 % level (see case study below). However, recent calibrations of standard ages and decay constants do vary at the 0.3 % level in the same time frame (Kuiper et al., 2008; Renne et al., 2011) and are particularly important to consider when comparing ages obtained using different chronometers.

Sampling procedures

Successful sampling for $^{40}Ar/^{39}Ar$ analyses requires careful preparation and implementation. Typical targets include volcanic ashes (e.g., tuffs) or lava flows that have been identified as having some relationship with the paleoanthropological material of interest. Accurate ages first and foremost require the careful documentation of stratigraphic and structural relationships between the dated unit and the horizons containing the archaeological evidence needing an age determination, as these field relationships ultimately control the significance of any obtained age constraints. Sampling volcanic ashes often requires care to avoid contamination from plant roots, both ancient and modern, which can rework sediments and introduce material of different ages into a sample. Success rates improve by examining a volcanic ash in a number of localities to identify the best one for sampling (i.e., the most crystal-rich and stratigraphically clear area). Lava flows can be variably altered, and success is improved by sampling the least altered regions.

Laboratory procedures

The first step of sample processing involves separating K-bearing minerals from a bulk volcanic ash or lava sample by crushing (if the sample is indurated), sieving, and separation of minerals based on magnetic and density properties. Ultimately, individual grains are visually selected for further analysis; this can involve from tens to hundreds of grains per sample. Lava flows may alternately be run as "whole-rock" or "groundmass" aliquots, where either the entire crushed sample or the groundmass is selected for further analysis. Groundmass analyses require the removal of any phenocrysts present in the sample. Selected grains are often treated with hydrofluoric (HF) acid to remove alteration and weathering products as well as any remaining volcanic glass from grain surfaces. One exception to this is biotite, the argon systematics of which can be affected by acid treatment. Following these procedures, the samples are wrapped in aluminum packets along with appropriate standards and sealed in a quartz glass tube. Standards used should be of an age similar to that of the sample. For example, when dealing with quaternary samples, many workers use the 1.2 Ma Alder Creek sanidine standard (Nomade et al., 2005; Renne et al., 2011). Samples and standards are then sent for irradiation, where they are placed in the core of a nuclear reactor and thus experience a neutron flux. This induces the nuclear reaction $^{39}K(n,p)^{39}Ar$, in which a neutron is captured by the ^{39}K atom and a proton is emitted, creating ^{39}Ar. A number of other interfering reactions also occur, for which corrections must be made.

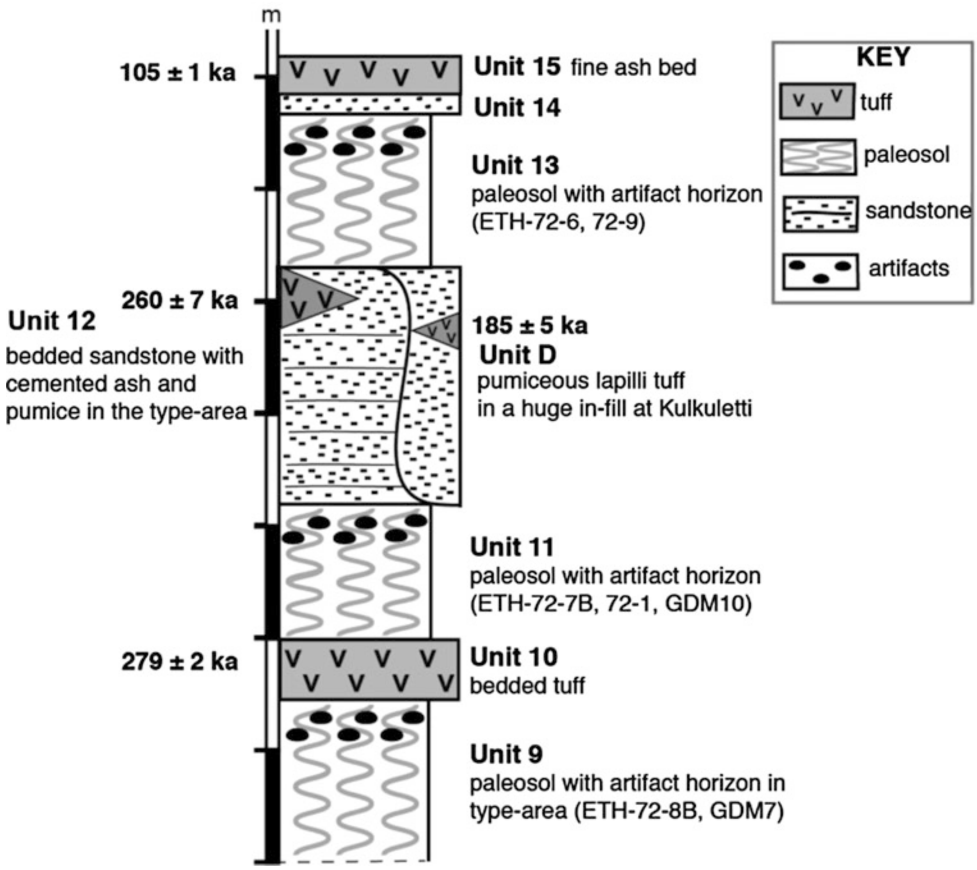
Following irradiation, samples and standard grains are transferred individually from irradiation packets into a disk for laser analyses (typically stainless steel or copper, with small pits for each grain), or foil packets for furnace analyses, which are loaded into the extraction line. The extraction line (which is directly connected to a noble gas mass spectrometer) is heated to ca. 100–150 °C under vacuum for at least several hours to decrease atmospheric argon contamination and reach pressure levels associated with an ultrahigh vacuum (ca. 10^{-9} mbar). Individual aliquots (typically single grains for volcanic ash samples) are then heated with a laser or furnace to release Ar from the grain. Laser analyses have lower "background" contamination than furnace analyses and thus are more commonly used for single-grain work.

The aim of total fusion analyses is to reach a temperature sufficient to release most Ar in a single step. Quantitative release of Ar is not necessary for age determinations. Incremental heating analyses (see above) begin at lower laser or furnace power; subsequent analyses increase that power sequentially. During and following heating (for either total fusion or incremental heating), released gas expands into an extraction line containing "getters" that trap reactive gases and thus serve to purify the noble gases (largely Ar) which do not react with getter material. Some laboratories also expose released gas to a "cryotrap," which freezes out water and other condensable phases.

Purified gas is subsequently expanded into a mass spectrometer, where atoms are ionized via an electron impact source, accelerated through a flight tube, turned and separated according to isotopic mass by a magnet, and then detected. Recent advances allow for the simultaneous detection of multiple isotopes via multicollector detector arrays, though many systems still in use produce excellent data with single collectors by employing peak-hopping methods to measure each isotope multiple times. Between sample and standard analyses, system blank values are measured by reproducing all steps apart from powering the laser or furnace; values determined for each isotope are subtracted from each sample and standard analysis. A correction is also made for mass-dependent isotopic fractionation (or "discrimination") in the mass spectrometer. This is achieved by comparing the difference between $^{40}Ar/^{36}Ar$ values in an aliquot of cleaned natural air and the known $^{40}Ar/^{36}Ar$ values of the terrestrial atmosphere, first estimated by Nier (1950) and updated by Lee et al. (2006). Although this is not always the case for historical ages, sufficient data should be published to allow for future age recalculation using different standard ages and half-life values. See Renne et al. (2009) for a complete description of reporting norms and requirements to allow for age recalculations using updated parameters.

"Absolute" ages, uncertainties, and comparisons with other methods

Age interpretation from any chronometer often relies on the ability to associate or calibrate the system with other chronometers or calendar years. Although some chronometers conventionally calculate ages relative to a particular time (e.g., ^{14}C), the K–Ar and $^{40}Ar/^{39}Ar$ systems yield ages relative to the time of analysis. As discussed above, calibration is dependent on the half-life of ^{40}K and standard ages applied to age calculations. Values for these parameters have been measured numerous times, and results can vary considerably between measurements (e.g., Beckinsale and Gale, 1969; McDougall and Roksandic, 1974; Steiger and Jäger, 1977; Renne et al., 1998; Min et al., 2000; Kuiper et al., 2008; Renne et al., 2010; McDougall and Wellman, 2011; Renne et al., 2011). Fortunately for paleoanthropological situations, relatively recent determinations (Kuiper et al., 2008; Renne et al., 2011) agree within 0.5 % of the age for relatively young samples (Renne, 2014), which is well within the geologic uncertainty (e.g., the association of dated material to the archaeological material) in most cases. Comparisons of legacy data with newer results, however, may require age recalculation to modern standard and decay constant values; this can be accomplished when sufficient analytical information has been provided.



^{40}Ar/^{39}Ar and K–Ar Geochronology, Figure 2 Composite stratigraphic section for Gademotta and Kulkuletti, Ethiopia. The ^{40}Ar/^{39}Ar method was used to constrain the ages of tephra from units 10, 12, and D. Artifacts found in Unit 9 are some of the oldest known Middle Stone Age artifacts in Africa. Reproduced with permission from Sahle et al. (2014).

Case study

Some of the earliest evidence for Middle Stone Age (MSA) archaeology in Africa is found in the Gademotta Formation near Ziway, Ethiopia. First excavated and dated by K–Ar in the 1970s by Fred Wendorf and colleagues (Wendorf and Schild, 1974), the ages of sites in the type locality and the nearby Kulkuletti area were revisited using the ^{40}Ar/^{39}Ar method in the 2000s (Morgan and Renne, 2008). Ages were obtained on sanidine crystals from two key tephras in the stratigraphy, Units 10 and D (Figure 2), and glass shard geochemistry linked the tephras between the two localities. The ^{40}Ar/^{39}Ar method yielded ages even older than those from K–Ar, likely due to incomplete degassing of feldspars during the K–Ar analyses. Artifacts found below Unit 10 (279 ± 2 ka) indicate that Gademotta contains some of the earliest known MSA artifacts. Renewed interest in the site led to further excavations (Sahle et al., 2013; Sahle et al., 2014), in which additional ^{40}Ar/^{39}Ar work yielded an age for a previously undated layer (Unit 12). Archaeological data indicate that the lowermost Gademotta site contains the earliest evidence for stone-tipped projectiles (Sahle et al., 2013).

Summary

K–Ar and ^{40}Ar/^{39}Ar geochronology exploit the decay of ^{40}K to ^{40}Ar. They have been used to constrain the ages of numerous paleoanthropological localities in areas with suitable volcanic deposits around the world. The age constraint is typically obtained for a volcanic rock interbedded or otherwise associated with archaeological and/or paleontological material, and thus the analyzed sample yields minimum or maximum ages for that material, depending on the association.

Bibliography

Aldrich, L. T., and Nier, A. O., 1948. Argon 40 in potassium minerals. *Physical Review*, **74**(8), 876–877.

Beckinsale, R. D., and Gale, N. H., 1969. A reappraisal of the decay constants and branching ratio of ^{40}K. *Earth and Planetary Science Letters*, **6**(4), 289–294.

Evernden, J. F., and Curtis, G. H., 1965. The potassium-argon dating of late Cenozoic rocks in East Africa and Italy. *Current Anthropology*, **6**(4), 342–385.
Fitch, F. J., and Miller, J. A., 1970. New hominid remains and early artefacts from northern Kenya: radioisotope age determinations of Lake Rudolf artefact site. *Nature*, **226**(5242), 226–228.
Fitch, F. J., Findlater, I. C., Watkins, R. T., and Miller, J., 1974. Dating of the rock succession containing fossil hominids at East Rudolf, Kenya. *Nature*, **215**(5472), 213–215.
Fitch, F. J., Hooker, P. J., and Miller, J. A., 1976. ^{40}Ar/^{39}Ar dating of the KBS tuff in Koobi Fora formation, East Rudolf, Kenya. *Nature*, **263**(5580), 740–744.
Hicks, A., Barclay, J., Mark, D. F., and Loughlin, S., 2012. Tristan da Cunha: constraining eruptive behavior using the ^{40}Ar/^{39}Ar dating technique. *Geology*, **40**(8), 723–726.
Jourdan, F., Matzel, J. P., and Renne, P. R., 2007. ^{39}Ar and ^{37}Ar recoil loss during neutron irradiation of sanidine and plagioclase. *Geochimica et Cosmochimica Acta*, **71**(11), 2791–2808.
Kuiper, K. F., Deino, A., Hilgen, F. J., Krijgsman, W., Renne, P. R., and Wijbrans, J. R., 2008. Synchronizing rock clocks of Earth history. *Science*, **320**(5875), 500–504.
Lanphere, M. A., and Dalrymple, G. B., 1966. Simplified bulb tracer system for argon analyses. *Nature*, **209**(5026), 902–903.
Lee, J.-Y., Marti, K., Severinghaus, J. P., Kawamura, K., Yoo, H.-S., Lee, J. B., and Kim, J. S., 2006. A redetermination of the isotopic abundances of atmospheric Ar. *Geochimica et Cosmochimica Acta*, **70**(17), 4507–4512.
McDougall, I., 1981. ^{40}Ar/^{39}Ar age spectra from the KBS Tuff, Koobi Fora Formation. *Nature*, **294**(5837), 120–124.
McDougall, I., and Harrison, T. M., 1999. *Geochronology and Thermochronology by the ^{40}Ar/^{39}Ar Method*, 2nd edn. New York: Oxford University Press.
McDougall, I., and Roksandic, Z., 1974. Total fusion ^{40}Ar/^{39}Ar ages using HIFAR reactor. *Journal of the Geological Society of Australia*, **21**(1), 81–89.
McDougall, I., and Wellman, P., 2011. Calibration of GA1550 biotite standard for K/Ar and ^{40}Ar/^{39}Ar dating. *Chemical Geology*, **280**(1–2), 19–25.
McDougall, I., Maier, R., Sutherland-Hawkes, P., and Gleadow, A. J. W., 1980. K–Ar age estimate for the KBS Tuff, East Turkana, Kenya. *Nature*, **284**(5753), 230–234.
Merrihue, C., and Turner, G., 1966. Potassium-argon dating by activation with fast neutrons. *Journal of Geophysical Research*, **71**(11), 2852–2857.
Min, K., Mundil, R., Renne, P. R., and Ludwig, K. R., 2000. A test for systematic errors in ^{40}Ar/^{39}Ar geochronology through comparison with U/Pb analysis of a 1.1-Ga rhyolite. *Geochimica et Cosmochimica Acta*, **64**(1), 73–98.
Morgan, L. E., and Renne, P. R., 2008. Diachronous dawn of Africa's Middle Stone Age: new ^{40}Ar/^{39}Ar ages from the Ethiopian Rift. *Geology*, **36**(12), 967–970.
Morgan, L. E., Renne, P. R., Taylor, R. E., and WoldeGabriel, G., 2009. Archaeological age constraints from extrusion ages of obsidian: examples from the Middle Awash, Ethiopia. *Quaternary Geochronology*, **4**(3), 193–203.
Morgan, L. E., Renne, P. R., Kieffer, G., Piperno, M., Gallotti, R., and Raynal, J. P., 2012. A chronological framework for a long and persistent archaeological record: Melka Kunture, Ethiopia. *Journal of Human Evolution*, **62**(1), 104–115.
Nier, A. O., 1935. Evidence for the existence of an isotope of potassium of mass 40. *Physical Review*, **48**(3), 283–284.
Nier, A. O., 1950. A redetermination of the relative abundances of the isotopes of carbon, nitrogen, oxygen, argon, and potassium. *Physical Review*, **77**(6), 789–793.
Nomade, S., Renne, P. R., Vogel, N., Deino, A. L., Sharp, W. D., Becker, T. A., Jaouni, A. R., and Mundil, R., 2005. Alder Creek sanidine (ACs-2): a quaternary ^{40}Ar/^{39}Ar dating standard tied to the Cobb Mountain geomagnetic event. *Chemical Geology*, **218** (3–4), 315–338.
Paine, J. H., Nomade, S., and Renne, P. R., 2006. Quantification of ^{39}Ar recoil ejection from GA1550 biotite during neutron irradiation as a function of grain dimensions. *Geochimica et Cosmochimica Acta*, **70**(6), 1507–1517.
Renne, P. R., 2014. Some footnotes to the optimization-based calibration of the ^{40}Ar/^{39}Ar system. *Geological Society, London, Special Publications*, **378**, 21–31.
Renne, P. R., Sharp, W. D., Deino, A. L., Orsi, G., and Civetta, L., 1997. ^{40}Ar/^{39}Ar dating into the historical realm: calibration against Pliny the Younger. *Science*, **277**(5330), 1279–1280.
Renne, P. R., Swisher, C. C., Deino, A. L., Karner, D. B., Owens, T. L., and DePaolo, D. J., 1998. Intercalibration of standards, absolute ages and uncertainties in ^{40}Ar/^{39}Ar dating. *Chemical Geology*, **145**(1–2), 117–152.
Renne, P. R., Deino, A. L., Hames, W. E., Heizler, M. T., Hemming, S. R., Hodges, K. V., Koppers, A. A. P., Mark, D. F., Morgan, L. E., Phillips, D., Singer, B. S., Turrin, B. D., Villa, I. M., Villeneuve, M., and Wijbrans, J. R., 2009. Data reporting norms for ^{40}Ar/^{39}Ar geochronology. *Quaternary Geochronology*, **4**(5), 346–352.
Renne, P. R., Mundil, R., Balco, G., Min, K., and Ludwig, K. R., 2010. Joint determination of 40K decay constants and ^{40}Ar*/^{40}K for the Fish Canyon sanidine standard, and improved accuracy for ^{40}Ar/^{39}Ar geochronology. *Geochimica et Cosmochimica Acta*, **74**(18), 5349–5367.
Renne, P. R., Balco, G., Ludwig, K. R., Mundil, R., and Min, K., 2011. Response to the comment by W. H. Schwarz et al. on "Joint determination of ^{40}K decay constants and ^{40}Ar*/^{40}K for the Fish Canyon sanidine standard, and improved accuracy for ^{40}Ar/^{39}Ar geochronology". *Geochimica et Cosmochimica Acta*, **75**(17), 5097–5100, doi:10.1016/j.gca.2011.06.021.
Sahle, Y., Hutchings, W. K., Braun, D. R., Sealy, J. C., Morgan, L. E., Negash, A., and Atnafu, B., 2013. Earliest stone-tipped projectiles from the Ethiopian Rift date to >279,000 years ago. *PLoS One*, **8**(11), e78092.
Sahle, Y., Morgan, L. E., Braun, D. R., Atnafu, B., and Hutchings, W. K., 2014. Chronological and behavioral contexts of the earliest Middle Stone Age in the Gademotta Formation, Main Ethiopian Rift. *Quaternary International*, **331**, 6–19.
Steiger, R. H., and Jäger, E., 1977. Subcommission on geochronology: convention on use of decay constants in geo- and cosmochronology. *Earth and Planetary Science Letters*, **36**(3), 359–362.
Wendorf, F., and Schild, R., 1974. *A Middle Stone Age Sequence from the Central Rift Valley, Ethiopia*. Wrocław: Zakład Narodowy im. Ossolińskich.

Cross-references

Isochron Dating
Pompeii and Herculaneum
Radiocarbon Dating
Tephrochronology
U-Series Dating

ARCHAEOLOGICAL STRATIGRAPHY

Julie K. Stein[1] and Vance T. Holliday[2]
[1]Burke Museum of Natural History and Culture, University of Washington, Seattle, WA, USA
[2]Anthropology and Departments Geosciences, University of Arizona, Tucson, AZ, USA

Introduction

Archaeologists have utilized stratigraphy in order to correlate sediment layers and archaeological assemblages for well over a century (Harris, 1989; Lyman and O'Brien, 1999; O'Brien and Lyman, 1999; Stein, 2000; Mills and Vega-Centeno, 2005). Relative-age determination based on the law of superposition and context is now used in essentially all archaeological excavations, and it is the foundation of almost every other dating technique as well as being more frequently applied than any other method. A site may contain hundreds of superimposed sediment layers, or built structures such as plazas, foundation walls, and streets, but in every case, stratigraphy is needed to interpret the age relationships of the artifacts and architecture. Stratigraphy is also crucial in reconstructing the landscape of occupation and past environments and in understanding *site formation processes* (see entry on Site Formation Processes in this volume). There have been few attempts to establish a systematic approach to archaeological stratigraphy and a nomenclature for its concepts and terms, however.

In contrast, geologists have compiled stratigraphic guides in response to the need "for uniform standards and common procedures in defining and classifying formal rock bodies, their fossils, and the time spans represented by them" (North American Commission on Stratigraphic Nomenclature, 2005, 1555). In these guides, the language used to denote rock units and their spatial and temporal relations has been formalized. In most geological stratigraphic guides, subdivisions of rock sequences are based on lithology (*lithostratigraphic units*), on fossil content (*biostratigraphic units*), and on the time periods in which rocks were deposited (*chronostratigraphic units*). Stratigraphic classification also includes soils and related weathering phenomena (*soil-stratigraphic* or "*pedostratigraphic*" *units*) and bounding discontinuities (*allostratigraphic units*) (see entries on Stratigraphy and Soil Stratigraphy in this volume) (North American Commission on Stratigraphic Nomenclature, 1983, 2005).

To establish stratigraphic schemes at archaeological sites, some archaeologists and geoarchaeologists have simply followed the rules of the *Code of Stratigraphic Nomenclature* established by geologists (North American Commission on Stratigraphic Nomenclature, 1983, 2005) or the *International Stratigraphic Guide* (Hedberg, 1976; Salvador, 1994; Murphy and Salvador, 2000). This can work as far as the Code goes, but it was established by and for geologists working with bodies of rock and spans of time longer than would be encompassed by most archaeological sites. Further, some archaeological sites contain geologic or occupation records that are very complex within very small areas (e.g., a cave or a tell). In geology, local complexities can be subsumed within the characteristics of larger bodies of rock. In archaeology, the localized geologic complexities of sites may be of particular interest because they have a direct bearing on interpreting the occupation record and the site formation processes. For example, local spring deposits may hold a crucial component of the archaeological record in a larger site, and thus establishing a nomenclature for those spring deposits is essential. Typical for many site stratigraphies are simple letter or number sequences (e.g., strata 1, 2, 3 or units A, B, C) with subdivisions (e.g., 1A, 1B or A1, A2). Formation/member terminology, following the North American Commission on Stratigraphic Nomenclature, has been applied in a few geoarchaeological situations (e.g., Laury and Albritton, 1975; Stafford, 1981; Haynes and Huckell, 2007).

Following the example of geologists, some archaeologists and geoarchaeologists have proposed a set of rules for clarifying terminology and classification in archaeological stratigraphy. Schiffer (1972, 1976, 1983, 1987) proposed a classification scheme for the archaeological record based on objects found within deposits rather than on the physical characteristics of the deposits themselves. Harris (1977, 1979, 1989; Harris et al., 1993) made a significant contribution when he proposed a modest classification system, with special emphasis on how to record stratigraphy. The "Harris Matrix" may be the best known and most widely applied archaeological stratigraphic classification system, but it is best applied in sites with a complex history of occupation with numerous features and abundant artifacts (see also papers in Roskams, 2000).

Gasche and Tunca (1983) were the first to propose a formal archaeological stratigraphic nomenclature based on geological guides as well as three separate formal units for archaeological strata based on lithology, artifactual content, and time periods. The purpose of Gasche and Tunca's guide is to "facilitate and even to stimulate the exchange and correlation of all information produced from archaeological sites . . . and to establish a cross-referencing system, which would be as objective as possible . . . and that would eliminate the ambiguities brought about by an arbitrary language" (Gasche and Tunca, 1983, 325).

Gasche and Tunca proposed three stratigraphic units for dividing archaeological sediments: (1) on the basis of lithology, i.e., lithologic units; (2) on artifactual content,

Archaeological Stratigraphy, Table 1 Formal stratigraphic terms used in geoarchaeology and geology

Classificatory basis	Stratigraphic classification Geoarchaeology	Formal subdivisions	Stratigraphic classification Geology	Formal subdivisions
Lithology (physical and/or	chemical composition)	Lithologic unit *Time-transgressive*	Layer Sub-layer Inclusion Elemental sediment unit	Lithostratigraphic unit *Time-transgressive*
Formation, member, bed				
Time	Chronostratigraphic unit *Specific time interval*	Set Phase Sub-phase	Geochronologic unit *Specific time interval*	Eon, era, period, epoch, age
Fossils	Biostratigraphic unit *Time-transgressive*	Biozone	Biostratigraphic unit *Time-transgressive*	Biozone
Artifacts	Ethnostratigraphic unit *Time-transgressive*	Zone Supra-zone Subzone	None	None

i.e., ethnostratigraphic units; and (3) on time periods, i.e., chronostratigraphic units. They argued that archaeostratigraphy can be accommodated by two additions to existing geologic stratigraphic guides and codes: (1) a lower-ranking lithostratigraphic unit called the Layer that would include subdivisions of strata useful for archaeology and microstratigraphy and (2) ethnostratigraphic units called the Zone, Supra-zone, and Subzone that would divide sequences of layers according to their artifactual content. This scheme has not been widely adopted, but it provides a good starting point for a broader discussion of archaeological stratigraphy (Table 1).

Lithologic units

A lithologic unit is a "three-dimensional body characterized by the general presence of a . . . (dominant) . . . lithologic type, or by the combination of two or more of these types, or even by the presence of other particularities that confer on the unit a homogeneous character. . .. Among other particularities, detailed attention should be paid to the lithologic content, the structure, texture, and color of the content, and the degree of erosion or denudation and their geometry" (Gasche and Tunca, 1983, 328, 329). In the archaeostratigraphic guide, the lithologic unit is equivalent to the *lithostratigraphic unit* in other geological stratigraphic guides and codes. Lithologic units are termed "Layers" (the basic unit used in stratigraphic correlations), "Sub-layers" (lithologic units that form part of a Layer), and "Inclusions" (smaller units that are part of a Layer or Sub-layer).

Although Gasche and Tunca (1983) were the first in archaeology to define a lithologic unit comprehensively, Fedele (1976, 1984) had suggested a similar unit earlier. Fedele defined an elemental sediment unit (ESU) as "a unit constituting the smallest geologically homogeneous entity as perceived in excavation . . . (and) contained between two consecutive recognizable discontinuities" (Fedele, 1976, 34). An ESU could be a stratigraphic division, a lateral (facies) differentiation, or a pedological horizon. An ESU is a ". . . formally named fact in the structure of a given site, whose mappable distribution can eventually be used as a marker" (Fedele, 1984, 11).

The proposal to adopt "lithologic unit" in geoarchaeology led to much discussion and some favorable reviews (Colcutt, 1987; Fedele and Franken, 1987; Farrand, 1984; Le Tensorer, 1984; Stein, 1987). The new unit was seen as needed due to (1) problems of scale; (2) disagreement as to the importance and nature of discontinuities in archaeological lithologic units, in contrast to the importance and nature of discontinuities in geological lithostratigraphic units; and (3) the need to describe archaeological sediments with attention to characteristics that are appropriate for archaeological stratigraphic inquiry. Stein (1990), however, argued that there was insufficient reason to propose a new type of lithostratigraphic unit. Rather, there was need for a formal lithostratigraphic unit (i.e., in the North American Commission on Stratigraphic Nomenclature) smaller than the existing unit of lowest rank (the Bed).

The first and most obvious dissimilarity between an archaeostratigraphic "Layer" and other lithostratigraphic units is in scale. The primary lithostratigraphic unit for geologists is the formation. Its spatial characteristics are purposely vague. The authors of the *International Stratigraphic Guide* say that "the thickness of units of formation rank follows no standard and may range from less than a meter to several thousand meters . . . [and that the] practicability of mapping and of delineation on cross sections is an important consideration in the establishment of formations" (Hedberg, 1976, 32). The authors of the *North American Stratigraphic Code* state that "thickness is not a determining parameter in dividing a rock succession into formations; the thickness of a formation may range from a feather edge at its depositional or erosional limit to thousands of meters elsewhere. . .. No formation is considered valid that cannot be delineated at the scale of geologic mapping practiced in the region where the formation is proposed" (North American Commission on Stratigraphic Nomenclature, 2005, 1569). Mappability is a crucial determinant in these two definitions. In archaeology, strata are differentiated in much the same way as in geology (i.e., on the basis of physical characteristics), but typically on the scale of a few meters down to centimeters or millimeters. Archaeological strata are also convenient for mapping at a scale appropriate for an archaeological site, but not always for a geologic region.

Layers that terminate laterally over short distances are common in archaeological sites (Tunca, 1987; de Meyer, 1984), and often they cannot be condensed into one general sequence (Cordy, 1987a). Correlations in stratigraphically complex archaeological sites frequently depend on the order of deposition of small disparate layers (discerned by recording overlapping edges) rather than on major stratigraphic units extending over the whole site. Thus, archaeologists do not expect to use "layers" in the same manner as geologists use "formations."

The importance and nature of discontinuities in archaeological stratigraphy generated some discussion, centering on an argument that discontinuities generated by humans are different from, and more numerous than, geologic discontinuities, and they therefore need their own terminology (Gasche and Tunca, 1983, 329). Logic argues that archaeological discontinuities should be described using a descriptive classification based on geologic terms (e.g., abrupt conformities, angular unconformities, disconformities).

Strata in archaeological contexts tend to be described in much the same way that sedimentologists describe sediments. Basic descriptors include grain size, grain shape, mineral composition, sedimentary structure, and color. Archaeologists have also examined distinctive attributes of cultural deposits to see if they are different from traditional sedimentological analyses. Schiffer (1987) proposed that, in addition to traditional sedimentological descriptions, certain attributes of artifacts are distinctive and diagnostic in the interpretation of cultural deposition (e.g., roundness of sherd edges). Stein and Teltser (1989) showed that grain-size distributions of separate compositional types of artifacts (e.g., ceramics, lithics, bone) provide a basis for interpretations of archaeological deposition (see also Fladmark, 1982; Rosen, 1986; Hull, 1987; Dunnell and Stein, 1989). Whether non-geological or cultural attributes are necessary in archaeological descriptions of sediment, a standardized, descriptive (nongenetic) terminology is necessary for the description of archaeological (and geological) stratigraphic relations.

An important similarity between the geoarchaeological lithologic unit and the geological lithostratigraphic unit is that they can be time-transgressive ("diachronic"), that is, the age of the upper or lower contacts, or both, is not necessarily the same everywhere. This can be due to varying rates and timing of sedimentation, localized erosion, or localized burial. The correlation of lithologic units does not mean that they are of the same age and, therefore, they may not contain archaeological materials or features of the same age.

Ethnostratigraphic units

Gasche and Tunca (1983, 331) proposed the term "ethnostratigraphic unit" for deposits identified on the basis of their anthropic content (i.e., artifacts). The terms "Zone" (the basic unit), "Supra-zone" (contains one or more Zones), and "Subzone" (subdivision of a Zone) are subdivisions of ethnostratigraphic units. Like the fossils that define biostratigraphic units, the artifacts of ethnostratigraphic units must be only those artifacts whose age of manufacture or use is coeval with the age of deposition of the strata, that is, the artifacts must be products of cultural activities taking place contemporaneously with the deposition.

To determine that an object was made or used concurrently with deposition requires that the observer determine the artifact's age and compare that with the age of the depositional event. Identification of an object as contemporaneous with deposition is, of course, an interpretation and a fundamental issue in fieldwork. Thus, because the goal of stratigraphy is to provide a descriptive system, selection of artifacts whose age of manufacture is contemporaneous with deposition is problematic. Clearly, correct interpretation of an artifact assemblage as contemporary with deposition depends on the training of the person examining the artifacts.

Archaeological stratigraphers follow the example of the *International Guide* and the *North American Stratigraphic Code*, by dividing strata that contain artifacts as distinct stratigraphic units on a level with lithostratigraphic and biostratigraphic units (Cordy, 1987a; Cordy, 1987b; Gasche and Tunca, 1983; Le Tensorer, 1984; van der Plas, 1987). Biostratigraphy and lithostratigraphy are recognized as means of subdividing a sequence of rocks based on different kinds of data. Lithostratigraphic units are subdivisions of rock bodies based on lithologic attributes, while biostratigraphic units are subdivisions-based biological attributes. Ethnostratigraphic units, therefore, are subdivisions of archaeological sediments (essentially unconsolidated rock) based on artifactual attributes. Artifacts accepted as being relevant to ethnostratigraphic description derive from artifact typologies and archaeological theory.

Gasche and Tunca (1983, 331) suggested that descriptions of ethnostratigraphic units be based on artifact classes. Lithologic units are characterized by the classes of artifacts they contain and then are regrouped such that all layers with the same classes of artifacts form one ethnostratigraphic unit. Gasche and Tunca did not discuss necessary conditions for defining a class of artifacts, however. Cordy (1987a, 1987b, 31) suggested that the artifact content of units is not the material on which ethnostratigraphy should be described. He suggested that culture (*entité palethnologique*) is the appropriate basis for definition. Cultures are interpreted from artifact assemblages, but archaeologists do not agree whether this is really possible (Willey and Phillips, 1958; Clarke, 1968; Dunnell, 1982; Binford, 1983; Watson et al., 1984).

Using artifact classes provides a more objective means for identifying ethnostratigraphic units, but such classes are not always standardized in a way that makes correlation from site to site possible. Different archaeologists with different research objectives might describe artifacts in grossly different ways and would certainly argue over the appropriateness of any given class, making stratigraphic correlations across regions extremely challenging. As with biostratigraphy and lithostratigraphy, archaeology needs a formal description of artifacts (separate from the concept of types and classes) that is routinely made at every site. A basic set of descriptive attributes on which all archaeologists would agree would be difficult to select, however. Archaeologists have been arguing about artifact classification for decades (e.g., Krieger, 1944; Spaulding, 1953; Ford, 1954).

Archaeologists routinely define so-called cultural groups on the basis of artifact assemblages, however. These seem to be reasonable approaches to ethnostratigraphy whether or not these groupings truly represent discrete cultures. Examples include a wide variety of ceramic assemblages representing cultural-historical groups such as those in the southwestern USA (e.g., Hohokam). Lithic assemblages are widely used to classify and subdivide archaeological records such as Paleo-Indian in North America (and subgroups such as Folsom and Clovis) or Paleolithic or Stone Age in the Old World (including Lower, Middle, and Upper Paleolithic as well as further subgroups such as Acheulean or Gravettian). The assemblages include descriptions of length, width, and shape of lithics and the temper, paste, surface decorations, and shape of ceramics. Once the assemblages are described and established, sequences of deposits can be grouped and divided on the basis of the presence, absence, or abundance of artifacts with certain attributes.

According to the archaeostratigraphic guide, ethnostratigraphic units are defined by the presence of the classes of artifacts that they contain. The decision about which classes are to be used is problematic, but it is best decided by someone trained in the theory and methodology of archaeology. As long as stratigraphers recognize that a body of rock can be subdivided by various schemes of classification, each independent of one another and developed for specific needs, ethnostratigraphic units should be considered as valid stratigraphic units distinct from lithostratigraphic or biostratigraphic units.

The use of artifacts, as opposed to deposits, to establish stratigraphic sequences in archaeology permits interpretations of reversed stratigraphy, and primary and secondary deposits. When labeling a sequence as "reversed," archaeologists are referring to the temporal order of the age of manufacture for objects contained in the deposit. The terms "primary" and "secondary" deposits describe the history of individual objects within the deposit rather than the deposit itself. The concept of secondary deposit in archaeology refers to the source of the individual artifacts within the deposit. A deposit is considered secondary when at least one of the artifacts within it was transported from another location where it was part of a primary deposit.

Like the lithologic unit, ethnostratigraphic units cannot be assumed to be the same age everywhere. They can be time-transgressive. Artifact assemblages can appear later or last longer in some areas, but not others. Unfortunately, artifact or assemblage correlations are routinely used to make numerical age correlations. Artifact assemblages *generally* can be the same age from place to place, but the timing of their appearance or disappearance cannot be assumed.

Chronostratigraphic units

"Chronostratigraphic units" are suggested as archaeological time-stratigraphic units that are characterized by their duration and by their temporal relations (Gasche and Tunca, 1983), similar to their use in formal geological stratigraphy. Chronostratigraphic units include one or several strata whose sedimentation took place during a specific time interval. The term "Phase" is proposed as the basic time unit. A phase is a grouping of adjacent strata of anthropic origins with a separate grouping of adjacent strata for those of natural origins. A "Set" is a group of phases, and a "Sub-phase" is a subdivision of a phase (1983, 330).

Gasche and Tunca (1983) only minimally discussed the chronostratigraphic unit, and they provided no valid arguments for accepting it as something different from geological chronostratigraphic units. Obviously, they considered the phase to be a subdivision of archaeological sediment that was deposited during a certain period of time, but they did not emphasize the difference (if any) between these sediments and geologic sediments. Rather than elaborate on the purpose of these units and how they differ from geological stratigraphy, Gasche and Tunca elaborated on the "constitution of chronostratigraphic units" (1983, 330). They detailed the manner in which a phase is to be grouped. They emphasized the need to separate deposits that have natural origins from those that have cultural origins and the need to distinguish from natural deposits those "… anthropic deposits whose sedimentation is caused by positive occupation by man (occupation of living floors) or negative occupation by man (filling, raising, etc.)" (p. 330). These preoccupations with natural versus cultural origins are another way of saying that they are subdividing the rocks by their artifact content or as ethnostratigraphic units. This perspective is an ethnocentric view of sedimentation, appropriate for creating ethnostratigraphic units, but it has nothing to do with chronostratigraphic units.

In both geology and archaeology, stratigraphers order strata in temporal sequences. In geology the temporal scale is often longer than in archaeology, but the difference is not sufficiently great to warrant, proposing a new time-stratigraphic unit. Lower-ranking time-stratigraphic units appropriate for archaeological stratigraphy are already inherent in the geologic stratigraphic codes. Both disciplines depend on superposition and isotopic dating to order strata, and both have problems with strata representing deposition that transgresses time (Watson and Wright, 1980).

Archaeological stratigraphy needs shorter but nevertheless formal time terms. In the Americas, for example, the Late Pleistocene and the Holocene, both formal components of the geologic time scale, encompass all of archaeological time; both terms are widely used, including subdivisions of the Holocene into Early, Middle, and Late. Formal definitions of those subdivisions were only recently proposed (Walker et al., 2012), however. In the Old World, chronostratigraphic subdivisions of the Pleistocene (Early, Middle, and Late) are widely used time terms and are well defined geologically (Gibbard and Cohen, 2008), but they span long temporal intervals.

With the advent of coring glaciers, shorter spans of time are being formalized for the Late Pleistocene. As formally defined, the Late Pleistocene began at the start of the last interglacial cycle (~130,000 years ago) and ended with the start of the Holocene. This interval encompassed a broad and complex array of behavioral and biological changes among hominins across Europe, Africa, and Asia, so chronostratigraphic subdivisions are useful. In the Americas, archaeological interest in the Late Pleistocene generally focuses on the final few millennia, so subdivisions are likewise useful. The Younger Dryas chronozone is a good example. Originally based on plant assemblages in northern Europe (a biostratigraphic unit), the term eventually became synonymous with a cold interval (a climatostratigraphic concept) in the last millennia of the Pleistocene. But plant assemblages and climate intervals are time-transgressive and not always globally synchronous nor even recognizable (Meltzer and Holliday, 2010). So now the Younger Dryas is most commonly intended as a time term (Björck, 2007) that is useful in both the Old and New Worlds.

Chronostratigraphic units in geoarchaeology, like their geologic equivalent, are not time-transgressive. Their upper and lower boundaries are the same age everywhere. For example, the lower boundary of the Holocene is about 10,000 radiocarbon years ago everywhere (Björck, 2007). Arguments over the age of the boundaries are normal and to be expected, but by definition they cannot be diachronic (shift around in time). The point of chronostratigraphic units is the designation of previously agreed-upon intervals of time. In our modern lives, each month has an agreed-upon beginning and end to serve our purposes of time keeping. If the beginning or end of chronostratigraphic units varied in time, the point of having such stratigraphic subdivisions would be defeated.

Summary

Archaeologists recognize the need to minimize ambiguity and clarify the distinctions among different kinds of stratigraphic units. To this end, Gasche and Tunca (1983) proposed an archaeostratigraphic guide, which introduced stratigraphic units: lithologic, ethnostratigraphic, and chronostratigraphic. The history and viability of archaeostratigraphy and proposed stratigraphic units was further examined and discussed by Stein (1987, 1990, 2000).

Gasche and Tunca proposed the "lithologic unit," similar to the lithostratigraphic units of geologic stratigraphic codes and guides, but subdivided into subunits with rankings of "Layer," "Sub-layer," and "Inclusion." The only characteristic of these subunits, however, that is different from previously proposed geologic lithostratigraphic units is the inferred difference in scale. Rather than proposing an entirely new lithologic unit with three ranks, Stein (1990) proposed that "Layer" suffice as a single, smaller-ranking unit of geological lithostratigraphy.

The "chronostratigraphic unit" discussed in the proposed archaeostratigraphic guide is not sufficiently different from geologic chronostratigraphic units to be justified. For purposes of archaeology, the chronostratigraphic and geochronologic units proposed in the various geological stratigraphic codes are adequate. Chronology is important in both archaeology and geology, and although the intervals of time on which each discipline focuses vary, the differences do not warrant creating a new chronostratigraphic unit for use in archaeology.

The "ethnostratigraphic unit" is a valid unit in which stratigraphic classifications of strata are based on their artifactual content. As with biostratigraphic units, divisions of ethnostratigraphic units are based on their content. The ethnostratigraphic unit requires a separate name because it involves separate theoretical and taxonomic principles. Although archaeologists may not yet agree as to the standardized description of artifact classes, the division of sediment sequences according to the presence of various artifacts is a valid stratigraphic practice and deserves to be recognized. Archaeologists have long used what could be described as ethnostratigraphic unit in various cultural-historical constructs.

Bibliography

Binford, L. R., 1983. *In Pursuit of the Past: Decoding the Archaeological Record*. New York: Thames and Hudson.

Björck, S., 2007. Younger Dryas oscillation, global evidence. In Elias, S. A. (ed.), *Encyclopedia of Quaternary Science*. Amsterdam: Elsevier, pp. 1985–1993.

Clarke, D. L., 1968. *Analytical Archaeology*. London: Methuen.

Colcutt, S. N., 1987. Archaeostratigraphy: a geoarchaeologist's viewpoint. *Stratigraphica Archaeologica*, **2**, 11–18.

Cordy, J.-M., 1987a. Modalités d'application de la stratigraphie à l'archéologie. *Stratigraphica Archaeologica*, **2**, 23–26.

Cordy, J.-M., 1987b. Réflexions sur l'ethnostratigraphie. *Stratigraphica Archaeologica*, **2,** 27–34.

De Meyer, L. (ed.), 1984. *Stratigraphica Archeologica*, 1. Archaeostratigraphic Classification and Terminology Workshop, Ghent, University of Ghent.

Dunnell, R. C., 1982. Science, social science, and common sense: the agonizing dilemma of modern archaeology. *Journal of Anthropological Research*, **38**(1), 1–25.

Dunnell, R. C., and Stein, J. K., 1989. Theoretical issues in the interpretation of microartifacts. *Geoarchaeology*, **4**(1), 31–41.

Farrand, W. R., 1984. More on stratigraphic practice. *Quarterly Review of Archaeology*, **5**(4), 3.

Fedele, F. G., 1976. Sediments as palaeo-land segments: the excavation side of study. In Davidson, D. A., and Shackley, M. L. (eds.), *Geoarchaeology*. Boulder, CO: Westview Press, pp. 23–48.

Fedele, F. G., 1984. Towards an analytical stratigraphy: stratigraphic reasoning and excavation. *Stratigraphica Archaeologica*, **1**, 7–15.

Fedele, F. G., and Franken, H. J., 1987. Report on the meeting in Brescia, Italy, July 5–8, 1984. *Stratigraphica Archaeologica*, **2**, 3–6.

Fladmark, K. R., 1982. Microdebitage analysis: initial considerations. *Journal of Archaeological Science*, **9**(2), 205–220.

Ford, J. A., 1954. The type concept revisited. *American Anthropologist*, **56**(1), 42–53.

Gasche, H., and Tunca, O., 1983. Guide to archaeostratigraphic classification and terminology: definitions and principles. *Journal of Field Archaeology*, **10**(3), 325–335.

Gibbard, P., and Cohen, K. M., 2008. Global chronostratigraphical correlation table for the last 2.7 million years. *Episodes*, **31**(2), 43–47.

Harris, E. C., 1977. Units of archaeological stratification. *Norwegian Archaeological Review*, **10**(1), 84–94.

Harris, E. C., 1979. *Principles of Archaeological Stratigraphy*. London: Academic.

Harris, E. C., 1989. *Principles of Archaeological Stratigraphy*, 2nd edn. London: Academic Press.

Harris, E. C., Brown, M. R., III, and Brown, G. J. (eds.), 1993. *Practices of Archaeological Stratigraphy*. London: Academic Press.

Haynes, C. V., and Huckell, B. B. (eds.), 2007. *Murray Springs: A Clovis Site with Multiple Activity Areas in the San Pedro Valley, Arizona*. Tucson: University of Arizona Press.

Hedberg, H. D. (ed.), 1976. *International Stratigraphic Guide: A Guide to Stratigraphic Classifications, Terminology, and Procedure*. New York: Wiley.

Hull, K. L., 1987. Identification of cultural site formation processes through microdebitage analysis. *American Antiquity*, **52**(4), 772–783.

Krieger, A. D., 1944. The typological concept. *American Antiquity*, **9**(3), 271–288.

Laury, R. L., and Albritton, C. C., Jr., 1975. Geology of middle stone age archaeological sites in the main Ethiopian Rift Valley. *Bulletin of the Geological Society of America*, **86**(7), 999–1011.

Le Tensorer, J.-M., 1984. L'archéostratigraphie: Problèmes méthodologiques et terminologiques, l'exemple de la fouille et des observations sur le terrain. *Stratigraphica Archaeologica*, **l**, 24–27.

Lyman, R. L., and O'Brien, M. J., 1999. Americanist stratigraphic excavation and the measurement of culture change. *Journal of Archaeological Method and Theory*, **6**(1), 55–108.

Meltzer, D. J., and Holliday, V. T., 2010. Would North American Paleoindians have noticed Younger Dryas age climate changes? *Journal of World Prehistory*, **23**(1), 1–41.

Mills, B. J., and Vega-Centeno, R., 2005. Sequence and stratigraphy. In Maschner, H. D. G., and Chippendale, C. (eds.), *Handbook of Archaeological Methods*. Lanham, MD: AltaMira Press, Vol. I, pp. 176–215.

Murphy, M. A., and Salvador, A. (eds.), 2000. International Subcommission on Stratigraphic Classification of IUGS International Commission on Stratigraphy. International Stratigraphic Guide—An abridged version. *GeoArabia* **5**(2), 231–266.

North American Commission on Stratigraphic Nomenclature, 1983. North American stratigraphic code. *American Association of Petroleum Geologists Bulletin*, **67**(5), 841–875.

North American Commission on Stratigraphic Nomenclature, 2005. North American stratigraphic code. *American Association of Petroleum Geologists Bulletin*, **89**(11), 1547–1591.

O'Brien, M. J., and Lyman, R. L., 1999. *Seriation, Stratigraphy, and Index Fossils: The Backbone of Archaeological Dating*. New York: Kluwer Academic/Plenum Publishers.

Rosen, A. M., 1986. *Cities of Clay: The Geoarchaeology of Tells*. Chicago: University of Chicago Press.

Roskams, S. (ed.), 2000. *Interpreting Stratigraphy: Site Evaluation, Recording Procedures and Stratigraphic Analysis*. Papers presented to the interpreting stratigraphy conferences, 1993–1997. Oxford: Archaeopress.

Salvador, A. (ed.), 1994. *International Stratigraphic Guide: A Guide to Stratigraphic Classifications, Terminology, and Procedure*, 2nd edn. Trondheim, Norway/Boulder, CO: International Union of Geological Sciences/Geological Society of America.

Schiffer, M. B., 1972. Archaeological context and systemic context. *American Antiquity*, **37**(2), 156–165.

Schiffer, M. B., 1976. *Behavioral Archeology*. New York: Academic Press.

Schiffer, M. B., 1983. Toward the identification of formation processes. *American Antiquity*, **48**(4), 675–706.

Schiffer, M. B., 1987. *Formation Processes of the Archaeological Record*. Albuquerque, NM: University of New Mexico Press.

Spaulding, A. C., 1953. Statistical techniques of the discovery of artifact types. *American Antiquity*, **18**(4), 305–313.

Stafford, T. W., Jr., 1981. Alluvial geology and archaeological potential of the Texas Southern high plains. *American Antiquity*, **46**(3), 548–565.

Stein, J. K., 1987. Deposits for archaeologists. *Advances in Archaeological Method and Theory*, **11**, 337–393.

Stein, J. K., 1990. Archaeological stratigraphy. In Lasca, N. P., and Donahue, J. (eds.), *Archaeological Geology of North America*. Boulder, CO: Geological Society of America. Centennial Special Volume, Vol. 4, pp. 513–523.

Stein, J. K., 2000. Stratigraphy and archaeological dating. In Nash, S. E. (ed.), *It's About Time: A History of Archaeological Dating in North America*. Salt Lake City: University of Utah Press, pp. 14–40.

Stein, J. K., and Teltser, P. A., 1989. Size distributions of artifact classes: combining macro- and micro-fractions. *Geoarchaeology*, **4**(1), 1–30.

Tunca, Ö., 1987. Stratigraphie en archéologie du Proche Orient. *Stratigraphica Archaeologica*, **2**, 35–39.

Van der Plas, L., 1987. Dust into dust, and under dust to lie: a discussion note on archaeostratigraphy. *Stratigraphica Archaeologica*, **2**, 19–22.

Walker, M. J. C., Berkelhammer, M., Björck, S., Cwynar, L. C., Fisher, D. A., Long, A. J., Lowe, J. J., Newnham, R. M., Rasmussen, S. O., and Weiss, H., 2012. Formal subdivision of the Holocene Series/Epoch: a discussion paper by a working group of INTIMATE (Integration of ice-core, marine and terrestrial records) and the Subcommission on Quaternary Stratigraphy (International Commission on Stratigraphy). *Journal of Quaternary Science*, **27**(7), 649–659.

Watson, R. A., and Wright, H. E., Jr., 1980. The end of the Pleistocene: a general critique of chronostratigraphic classification. *Boreas*, **9**(3), 153–162.

Watson, P. J., LeBlanc, S. A., and Redman, C. L., 1984. *Archeological Explanation: The Scientific Method in Archeology*. New York: Columbia University Press.

Willey, G. R., and Phillips, P., 1958. *Method and Theory in American Archaeology*. Chicago: University of Chicago Press.

Cross-references

Chronostratigraphy
Climatostratigraphy
Harris Matrices and the Stratigraphic Record
Sedimentology
Site Formation Processes
Soil Stratigraphy
Stratigraphy

ARCHAEOMAGNETIC DATING

Stacey Lengyel
Illinois State Museum, Springfield, IL, USA

Synonyms

Archaeointensity dating; Archaeomagnetism; Directional dating; Magnetic dating

Definition

Archaeomagnetism. The study of the magnetic properties of archaeological materials.

Archaeomagnetic dating. The dating of archaeological materials that retain fossilized records of the Earth's magnetic field by comparing the direction and/or strength of the material's magnetism with known records of changes in the Earth's magnetic field through time.

Geomagnetic secular variation. Changes in the strength and direction of the Earth's magnetic field with periods of a year to millions of years (Merrill et al., 1998); not to be confused with polar reversals, which have periodicities of hundreds of thousands to millions of years.

Introduction

At its root, archaeomagnetic dating grew out of the early observations that fired materials become magnetized parallel to the ambient magnetic field (Boyle, 1691; Gilbert, 1958) and that the geomagnetic field changes through time (Halley, 1692; see Tarling, 1983). More focused research in the late nineteenth and early twentieth centuries on the magnetization of baked clays and lava flows (Melloni, 1853; Folgheraiter, 1899; Mercanton, 1918; Chevallier, 1925) further refined and linked these observations, providing the foundation for modern paleomagnetic studies, including archaeomagnetism. As a discipline, archaeomagnetic studies were firmly established through the work conducted by Émile Thellier and his students between 1930 and 1960 (Thellier, 1936, 1938; Thellier and Thellier, 1959). During this period, these researchers explored and described the magnetic properties of baked clays, developed sampling techniques for recovering archaeomagnetic materials from the field, and designed and developed laboratory equipment and techniques for analyzing archaeomagnetic samples. By 1960, these methods had been greatly refined, and archaeomagnetic studies were undertaken in various parts of Europe (Cook and Belshé, 1958; Aitken, 1958), Japan (Watanabe, 1959), and the Soviet Union (Burlatskaya and Petrova, 1961). A few years later, the technique was introduced to archaeologists working in the American Southwest (Dubois and Watanabe, 1965), and by 1967 it was being used to date archaeological sites throughout that region (Weaver, 1967).

Today, archaeomagnetic dating is well established throughout Europe (Kovacheva et al., 1998; Le Goff et al., 2002; Schnepp and Lanos, 2005; Zananiri et al., 2007), the American Southwest (LaBelle and Eighmy, 1997; Lengyel, 2010), and parts of Mesoamerica (Wolfman, 1990; Hueda-Tanabe et al., 2004), and it is finding increasing success in areas such as the Middle East (Speranza et al., 2006), Northern Africa (Rimi et al., 2004), the American midcontinent (Lengyel, 2004), and parts of South America (Goguitchaichvili et al., 2011; Lengyel et al., 2011). Until recently, the majority of this work had been undertaken by paleomagnetists and geophysicists, who are primarily interested in using archaeomagnetic data to examine changes in the Earth's magnetic field over time. To a lesser extent, archaeological interest in the technique as an alternative dating method has either enabled or driven the development of the technique (Eighmy and Sternberg, 1990). New collaborations between these two groups of researchers – see, for example, the papers in Batt and Zananiri (2008) – have led to more synergistic approaches to archaeomagnetic dating.

Archaeomagnetic principles

Archaeomagnetic dating depends on two related phenomena. First, the Earth's magnetic field changes in strength (intensity) and direction (inclination and declination) through time (i.e., geomagnetic secular variation), with significant changes occurring on the order of decades to centuries. Second, the soils that make up many archaeological features contain ferromagnetic minerals, such as hematite and magnetite, that can record the direction and strength of the geomagnetic field under certain conditions. By comparing the magnetization recorded by an archaeological feature to a calibrated record of secular variation, the age of the feature can be estimated. If the global geomagnetic field was produced by a simple geocentric dipole, similar to a bar magnet at the center of the Earth, it would be uniformly distributed, and a global model of geomagnetic field change through time could be used to determine when an archaeological feature was magnetized. However, only 80–90 % of the geomagnetic field at the Earth's surface can be ascribed to an inclined geocentric dipole. The remaining 10–20 % of the observed geomagnetic field is variably distributed across the global surface and concentrated primarily within six or seven continent-sized features that grow, shrink, and move through time. This is the non-dipole field, and it may add to, subtract from, or have no effect on the main dipole field in any given location. This heterogeneity of the non-dipole field necessitates the use of region-specific secular variation records for areas separated by several thousand kilometers. Thus, the age of magnetization can be ascertained only in areas for which this record has been established.

Typically, archaeological artifacts and features acquire a magnetization through heating. This thermoremanent magnetization (TRM) is acquired when archaeological materials are heated close to or above mineralogically specific temperatures (i.e., Curie temperatures; 580 °C for magnetite, 680 °C for hematite) and then cooled to ambient temperatures. As these materials cool below the Curie temperature, the ferromagnetic minerals will become magnetized parallel to the prevailing magnetic field. The material can retain this remanent magnetization unless it is reheated to a similar temperature, at which point a new magnetization will be acquired. Additionally, the material must remain stationary after magnetization in order to preserve the directional orientation (the declination and inclination) of the acquired remanence; the intensity of the remanence, however, is unaffected by physical movement. For this reason, archaeodirectional studies can be used to date stationary archaeological contexts only, such as fire pits, burned structures, or kilns, while archaeointensity studies can focus on portable objects, such as bricks and pottery, in addition to in situ archaeological features. It should be noted that archaeointensity tends to be less faithfully recorded than archaeodirection by some archaeological materials, and the identification of suitable materials is currently a hot topic in archaeointensity studies (Casas et al., 2005; Ben-Yosef et al., 2008; Shaar et al., 2010; Morales et al., 2011).

In some cases, anthropogenic water transport or containment features, such as canals or reservoirs, can acquire a depositional remanent magnetization (DRM) or postdepositional remanent magnetization (pDRM), which occurs when ferromagnetic grains physically rotate as they settle subaqueously during and/or after deposition to align with the geomagnetic field. As deposits accumulate, it becomes physically difficult for the grains that have been buried to continue rotating, and the magnetization acquired during or shortly after deposition becomes locked in. These types of features are encountered, and archaeomagnetically dated, much less frequently than thermal features (Eighmy and Howard, 1991).

For a more in-depth discussion of remanent magnetism and basic archaeomagnetic principles, see Tarling (1983), Butler (1992), and Merrill et al. (1998).

Sampling methodologies

A variety of terminologies and sampling methodologies have been developed for recovering appropriate materials for archaeomagnetic dating (see Lanos et al., 2005; Trapanese et al., 2008). In all cases, the sampled material relates to a specific archaeological context that is assumed to have been homogeneously magnetized during a single event. For some researchers in the USA, the context is referred to as a feature, and the recovered material is referred to as a single archaeomagnetic sample, which is composed of multiple specimens. In most other regions, the context is referred to as a site from which multiple samples are recovered. In all cases, successful sampling begins with the identification of appropriate contexts for dating, taking into consideration the extent of firing (or deposition), the inclusion of appropriate ferromagnetic minerals, the size and preservation of the context, and, for directional studies, the integrity of the context (see Eighmy, 1990, for a thorough discussion).

For directional studies, sampling methods have been designed to remove individual pieces of material in such a way as to preserve the in situ orientation of the magnetized grains. Typically, between 6 and 20 oriented samples are recovered from a single context, providing a statistically valid dataset for the feature that can be used to calculate the mean direction of the magnetic remanence. This sample size has also been shown to minimize the effects of magnetic noise and random errors on the averaging statistics (Tarling and Dobson, 1995). In many cases, collectors employ some version of the original technique developed by Thellier (1967), which involves isolating material for recovery, with or without the use of square molds, encasing the material in nonmagnetic plaster or plastered bandages (Schnepp et al., 2008), marking the sample orientation on the plaster, and then removing the samples to the lab for further consolidation and subsampling. Typically, subsampling involves cutting anywhere from 1 to 20 cubic specimens (~4–27 cm^3) from each of the oriented samples (Kovacheva and Toshkov, 1994; Schnepp et al., 2004). In the USA, separate specimens are oriented and collected in the field, and the roughly 15 cm^3 specimens arrive in the laboratory ready for analysis (Eighmy, 1990). In the UK, collectors typically glue 2.5 cm plastic disks, leveled with a spirit level, to the flattened surface of well-consolidated material, mark the sample orientation on the disk, and then remove the disk with attached material to the lab for analysis. For less consolidated materials, these collectors push small plastic tubes (2.5 cm in diameter) into the material, mark the orientation, and then remove and seal the tubes before transporting them to the lab (Clark et al., 1988; Linford, 2006). For very hard materials, such as bricks or extremely well-fired kiln floors, samples can be removed with the standard water-cooled drilling method employed by most paleomagnetists (Collinson, 1983; Butler, 1992). In all cases, samples are oriented prior to removal, typically with a magnetic compass or a sun compass.

Archaeointensity sampling is less complicated and typically proceeds much more quickly, since the samples do not need to be oriented. Prepared specimens may be similar in size and shape to those collected for archaeodirectional analysis, or they may be smaller ~1 cm^3 microsamples (Donadini et al., 2008).

Laboratory procedures

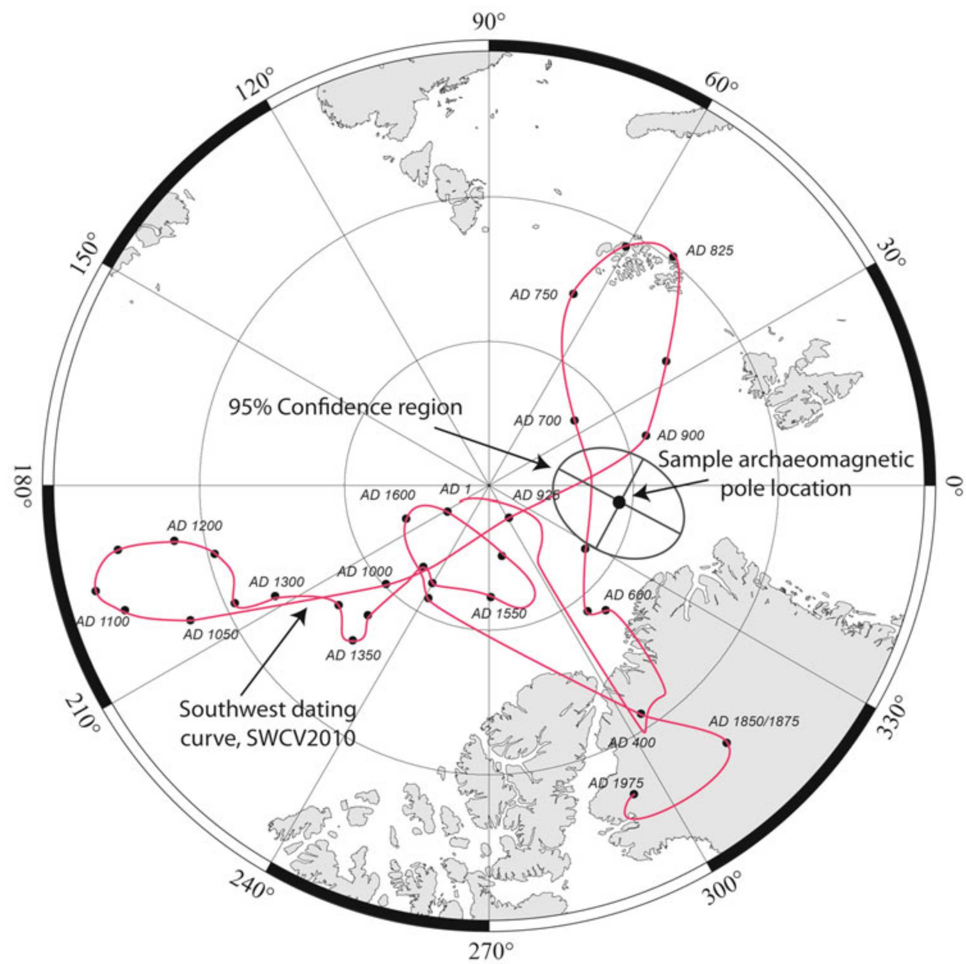
Archaeomagnetic laboratories have developed a number of techniques for isolating and measuring the characteristic remanent magnetization (ChRM) that is carried by archaeomagnetic samples. This is the primary magnetization that was acquired during the heating or depositional event of interest, and it is the information that must be retrieved in order to date the archaeological context. Over time, primary magnetization is overprinted with weaker and/or unstable secondary magnetic components that must be removed before the sample's ChRM can be determined. Typically, this is achieved by subjecting the individual specimens to sinusoidally decaying, weak alternating magnetic fields (AF demagnetization) or heating to low temperatures and then cooling within a zero magnetic field (thermal demagnetization). Both of these techniques have the effect of randomizing the magnetization of weak or unstable magnetic grains, effectively zeroing their contribution to the sample's overall magnetization. Most laboratories will measure the specimens prior to demagnetization in order to establish their baseline magnetization or natural remanent magnetization (NRM). Measurement is done with either a spinner or cryogenic magnetometer. Once the NRM is established, the demagnetization experiment begins by subjecting the specimen to low-level alternating fields, typically on the order to 5–10 mT (millitesla), or heating it to 50–100 °C. The specimen is then remeasured in the magnetometer, before being demagnetized at a higher temperature or peak field strength. Typically, labs will progressively demagnetize and remeasure specimens over a sequence of increasing temperatures or peak field strengths until the secondary components are removed. The changes in strength and direction that are measured over the course of demagnetization are statistically analyzed using principal component analysis (Kirschvink, 1980) to determine the specimen's primary direction of magnetization. Specimens that exhibit too much variation over the course of demagnetization are considered unstable and are excluded from further statistical analysis. Once the ChRM has been determined for each specimen, the results from all specimens are statistically averaged (Fisher, 1953) to calculate the mean direction of magnetic remanence, and associated error, for the sample. These values are then used to date the associated feature (see below).

Until recently, most labs routinely measured only the direction of the acquired magnetic remanence, due to the difficulties in reliably determining archaeointensities. However, the potential value of archaeointensity determinations, both for paleomagnetic field investigations (e.g., global field reconstructions) and archaeomagnetic dating purposes, has led several researchers to focus on improving the procedures used to determine these values (Le Goff and Gallet, 2004; Chauvin et al., 2005; Donadini et al., 2007, 2008; Ben-Yosef et al., 2008; Shaar et al., 2010). In theory, the strength of a sample's TRM (J) will be linearly proportional to the strength of the ancient geomagnetic field (H) that was present during cooling, such that $H = J/\chi_{TRM}$, where χ_{TRM} is a proportionality constant that indicates the material's susceptibility to TRM acquisition. Thus, by measuring the sample's intensity and then determining its proportionality constant by heating and cooling it within a known magnetic field, the intensity of the ancient geomagnetic field could be calculated. This straightforward approach presumes, however, that the sample retains a single magnetic component and that the magnetic mineralogy has remained unaltered since initial TRM acquisition, conditions that are rarely met in practice. Therefore, a much more complicated and time-consuming experiment is needed to establish the proportionality constant and estimate the paleointensity of the ancient field. Typically, researchers employ some form of the original experiment designed by Thellier (1938) and Thellier and Thellier (1959), in which individual specimens are repeatedly heated and cooled within a known field at increasing temperature intervals, twice at each temperature, in order to determine the range of temperatures over which the proportionality ratio remains constant. A variety of checks are employed throughout the experiment to monitor for laboratory-induced thermochemical alterations as well as the effects of nonideal magnetic grain sizes, cooling rates, and anisotropy of the specimen material (see Donadini et al., 2007). The experiment is repeated for all specimens in a sample, and a mean archaeointensity is calculated for the sample from a subset yielding statistically consistent results.

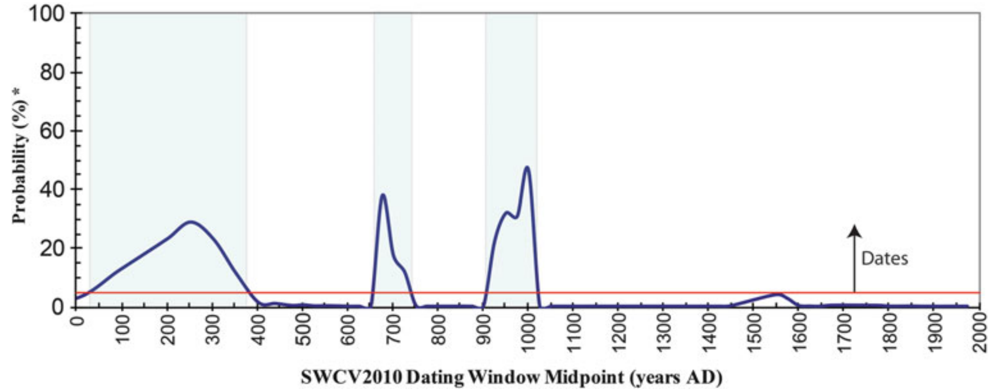
Secular variation curves

Archaeomagnetic data obtained from an archaeological feature can be used to estimate that feature's calendrical age by comparing the data to a calibrated reconstruction of secular variation, often referred to as an archaeomagnetic reference curve. The reference curve can be depicted either as changes in inclination (I), declination (D), and, if available, paleointensity through time (Schnepp and Lanos, 2005; Zananiri et al., 2007) or as changes in the location of the virtual geomagnetic pole through time (Lengyel, 2010). Because secular variation changes randomly and the geomagnetic pole appears to "wander" spatially over time, reference curves are created from sources such as historically recorded direct observations of the field (Barraclough, 1994; Jackson et al., 2000; Korte et al., 2009), archaeomagnetic measurements of independently dated archaeological features (LaBelle and Eighmy, 1997; Zananiri et al., 2007; Valet et al., 2008), paleomagnetic measurements of dated sediment deposits (Nilsson et al., 2010) or lava flows (Hagstrum and Champion, 2002), or some combination of the above (Lengyel, 2004; Finlay, 2008; Hagstrum and Blinman, 2010). Archaeomagnetic or paleomagnetic data included in these datasets must be dated independently through other techniques, such as dendrochronology or radiocarbon dating, and precision criteria often require these data to have independent date ranges of 200 years or less (e.g., LaBelle and Eighmy, 1997: 432).

Furthermore, these curves can be calculated from either a regional dataset (Zananiri et al., 2007) or directly from a global model (Lodge and Holme, 2009). Curves that are based on regional datasets are typically calculated by smoothing archaeomagnetic data from within a 1,000 km area through some form of running average (Sternberg and McGuire, 1990; Le Goff et al., 2002) or within a Bayesian statistical framework (Lanos et al., 2005). Each of these methods utilizes some form of the conversion-via-pole method (Noel and Batt, 1990), which allows researchers to relocate archaeomagnetic data recovered from localities scattered across a region to a single reference location, such as London in the UK or Paris in France. This is done for each pair of measured declination and inclination values by first calculating the virtual geomagnetic pole for that pair of values at the respective sampling site and then calculating the subsequent declination and inclination values for that same virtual geomagnetic pole from the reference locality. In some studies, particularly those in the USA, the regional archaeomagnetic data are simply converted to virtual geomagnetic poles, and subsequent calculations use these pole positions rather than the converted declination and inclination data. It has been shown, however, that the relocation of data to a central location introduces potentially significant geographic error (Casas and Incoronato, 2007). As has been demonstrated recently, this error can be avoided by calculating local reference curves directly from global models, a method that has the added benefit of producing reference curves for specific locations, such as an archaeological site (Lodge and Holme, 2009). Because data coverage varies between global models, it



Archaeomagnetic Dating, Figure 1 Archaeomagnetic sample data plotted against the American Southwest reference curve SWCV2010. This figure illustrates the regional secular variation curve for the American Southwest between AD 1 and AD 2000, and it depicts the virtual locations of the geomagnetic pole over that interval. Note the prominent loops in the curve at roughly AD 400, AD 825, AD 1125, and AD 1550. The sample data plots near a crossover in the curve at roughly AD 675 and AD 910, thereby intersecting more than one segment of the curve. This is a common situation in archaeomagnetic dating and results in more than one possible date range for the archaeomagnetic sample. Unlike radiocarbon date calibration, each archaeomagnetic date range obtained from the reference curve constitutes a unique 95 % probability range for that sample. Typically, other sources of chronometric data are consulted to determine which archaeomagnetic date range provides the best age estimate for the sampled archaeological context.



Archaeomagnetic Dating, Figure 2 Mathematically derived 95 percent probability curve for the archaeomagnetic sample data plotted in Fig. 1 when compared to the SWCV2010 reference curve data via Sternberg and McGuire's (1990) statistical method. Spikes in the probability curve above the 5 percent significance line indicate time periods during which there is no statistically measureable difference between the sample data and the curve data. In other words, these are the time periods during which the sample data is said to "date" against the reference curve. Each spike constitutes an individual 95 percent date range for the respective sample.

may be less robust for some areas and/or time periods than is currently available through regional datasets, limiting the application of this method.

Dating methodologies

The creation of archaeomagnetic reference curves and the dating of archaeomagnetic samples both rely on the underlying principle that archaeomagnetic materials that are the same age should exhibit similar geomagnetic characteristics. Thus, the data obtained from an archaeomagnetic sample can be compared to those of a calibrated reference curve for the region in question in order to ascertain the time periods during which both exhibit the same directional and/or intensity characteristics (Figure 1). This can be done visually or mathematically. The visual method is intuitively obvious and involves plotting the sample data and confidence limits against the regional reference curve. Visual inspection reveals the time period(s) during which the sample data were most similar to the magnetic field location and/or intensity, indicating the best-fit date range(s) for the associated archaeological feature. A greater variety of mathematical methods is available for estimating a sample's date range (Sternberg and McGuire, 1990; Le Goff et al., 2002; Lanos, 2004; Pavón-Carrasco et al., 2011; e.g., Figure 2), and in most cases these methods are preferred over the visual one due to their greater objectivity and the replicability of their results. However, the use of these methods is dependent on the availability of appropriately constructed reference curves with associated measures of uncertainty. Regardless which method is used, multiple dating solutions are often obtained because the path of secular variation loops back on itself through time, making it likely that sample data will match more than one segment of the reference curve. The use of the full magnetic vector for dating (i.e., both directional and intensity data) can alleviate this ambiguity, but the relatively limited spatial and temporal coverage of intensity curves currently restricts this approach to regions such as Central Europe (e.g., Kostadinova and Kovacheva, 2008). In most regions, researchers are advised simply to select the most likely dating option based on other archaeological evidence from the site.

Because archaeomagnetic data can be related directly to specific anthropogenic events, they lend themselves to addressing interesting archaeological dating questions. Typically, archaeomagnetic data are used to assess the age of individual archaeological features, such as kilns, furnaces, ovens, and hearths (Zhaoqin and Noel, 1989; Riisager et al., 2003; Jordanova et al., 2004; Casas et al., 2007), which have acquired the observed magnetic remanence during normal use. In some cases, archaeomagnetic data may provide one of the few methods for dating a specific context, such as unfired lime-plaster surfaces (Hueda-Tanabe et al., 2004) or hematite-pigment-painted murals (Zanella et al., 2000). Furthermore, archaeomagnetic data are especially well suited for reconstructing the use history of complex thermal sites such as glass-making installations (Linford and Welch, 2004), metallurgical workshops (Hus et al., 2004), and ceramic potteries (Kovacheva et al., 2004; De Marco et al., 2008), for which data from multiple features can be obtained and compared. Likewise, archaeomagnetic data recovered from multiple features at a single site can be used to resolve questions about a site's stratigraphy (Jordanova et al., 2004) or to address complex questions of site use through time (Donadini et al., 2012). In the American Southwest, in particular, it is not uncommon for extremely large suites of archaeomagnetic data to be recovered from numerous features ($N > 25$) across a single site for the express purpose of reconstructing the use history of the site, including the identification of different periods of occupation within a site's history and the ability to relate contemporaneous features across a large site (Sternberg et al., 1991; Chenault and Ahlstrom, 1993; Eighmy and Mitchell, 1994; Henderson, 2001; Deaver and Whittlesey, 2004; Lengyel, 2011). Finally, at even greater scales, archaeomagnetic data recovered from across archaeological culture areas may be used to assess and constrain cultural chronologies and the timing of archaeological phases within those chronologies. This has been particularly useful in the American Southwest, where archaeomagnetic data have played a key role in defining the Hohokam cultural chronology (Dean, 1991).

Summary

Archaeomagnetic dating uses changes in the Earth's magnetic field through time to date archaeological contexts such as kilns, fire pits, and canals. These contexts acquire a remanent magnetization parallel to the ambient geomagnetic field under conditions such as firing to relatively high temperatures or fluvial deposition, and the magnetization is retained unless the material is reheated or disturbed. The context is dated by comparing its remanent magnetization to a calibrated record of geomagnetic secular variation, using the principle that contemporary archaeomagnetic materials will share similar geomagnetic characteristics. Until recently, researchers typically used only the directional component of the remanent magnetization to date archaeological contexts. However, renewed recognition of the value of utilizing the full vector for dating, as well as for geomagnetic field reconstructions, has prompted several researchers to focus on improving the methodology used to determine paleointensity values and to advocate for expanding the spatial and temporal coverage of paleointensity records.

Bibliography

Aitken, M. J., 1958. Magnetic dating. *Archaeometry*, **1**(1), 16–20.

Barraclough, D. R., 1994. Observations of the Earth's magnetic field made in Edinburgh from 1670 to the present day. *Transactions of the Royal Society of Edinburgh: Earth Sciences*, **85**(4), 239–252.

Batt, C. M., and Zananiri, I. (eds.), 2008. Archaeomagnetic applications for the rescue of cultural heritage (AARCH). *Physics and Chemistry of the Earth, Parts A/B/C*, **33**(6–7), 403–608.

Ben-Yosef, E., Tauxe, L., Ron, H., Agnon, A., Avner, U., Najjar, M., and Levy, T. E., 2008. A new approach for geomagnetic archaeointensity research: insights on ancient metallurgy in the southern Levant. *Journal of Archaeological Science*, **35**(11), 2863–2879.

Boyle, R., 1691. *Experimenta %26 Observationes Physicae*. London: Printed for J. Taylor and J. Wyat.

Burlatskaya, S. P., and Petrova, G. N., 1961. Pervye rezul'taty izucheniya geomagnitnogo polya v proshlom «arkheomagnitnym» metodom [First results of a study of the geomagnetic field in the past by the "archaeomagnetic" method. *Geomagnetizm i aeronomiya [Geomagnetism and Aeronomy]*, **1**(2), 233–236 (In Russian).

Butler, R. F., 1992. *Paleomagnetism: Magnetic Domains to Geologic Terranes*. Boston: Blackwell Scientific Publications.

Casas, L., and Incoronato, A., 2007. Distribution analysis of errors due to relocation of geomagnetic data using the 'Conversion via Pole' (CVP) method: implications on archaeomagnetic data. *Geophysical Journal International*, **169**(2), 448–454.

Casas, L., Shaw, J., Gich, M., and Share, J. A., 2005. High-quality microwave archaeointensity determinations from an early 18th century AD English brick kiln. *Geophysical Journal International*, **161**(3), 653–661.

Casas, L., Linford, P., and Shaw, J., 2007. Archaeomagnetic dating of Dogmersfield Park brick kiln (Southern England). *Journal of Archaeological Science*, **34**(2), 205–213.

Chauvin, A., Roperch, P., and Levi, S., 2005. Reliability of geomagnetic paleointensity data: the effects of the NRM fraction and concave-up behavior on paleointensity determinations by the Thellier method. *Physics of the Earth and Planetary Interiors*, **150**(4), 265–286.

Chenault, M. L., and Ahlstrom, R. V. N., 1993. Chronology. In Chenault, M. L., Ahlstrom, R. V. N., and Motsinger, T. N. (eds.), *In the Shadow of South Mountain: The Pre-classic Hohokam of La Ciudad de Los Hornos*. Tucson: SWCA. SWCA Archaeological Report 93–30, pp. 579–586.

Chevallier, R., 1925. L'aimantation des laves de l'Etna et l'orientation du champ terrestre en Sicile du XII[e] au XVII[e] siècle. *Annales de Physique*, **4**, 5–162.

Clark, A. J., Tarling, D. H., and Noël, M., 1988. Developments in archaeomagnetic dating in Britain. *Journal of Archaeological Science*, **15**(6), 645–667.

Collinson, D. W., 1983. *Methods in Rock Magnetism and Palaeomagnetism: Techniques and Instrumentation*. London: Chapman and Hall.

Cook, R. M., and Belshé, J. C., 1958. Archaeomagnetism: a preliminary report from Britain. *Antiquity*, **32**(127), 167–178.

De Marco, E., Spassov, S., Kondopoulou, D., Zananiri, I., and Gerofoka, E., 2008. Archaeomagnetic study and dating of a Hellenistic site in Katerini (N. Greece). *Physics and Chemistry of the Earth*, **33**(6–7), 481–495.

Dean, J. S., 1991. Thoughts on Hohokam chronology. In Gumerman, G. (ed.), *Exploring the Hohokam: Prehistoric Desert Peoples of the American Southwest*. Albuquerque: University of New Mexico Press, pp. 61–150.

Deaver, W. L., and Whittlesey, S. M., 2004. Archaeomagnetic dating. In Whittlesey, S. M. (ed.), *Pots, Potters, and Models. Archaeological Investigations at the SRI Locus of the West Branch Site, Tucson, Arizona, Vol. 2: Synthesis and Interpretations*. Tucson: Statistical Research. Statistical Research, Technical Series 80, pp. 101–134.

Donadini, F., Riisager, P., Korhonen, K., Kahma, K., Pesonen, L., and Snowball, I., 2007. Holocene geomagnetic paleointensities: a blind test of absolute paleointensity techniques and materials. *Physics of the Earth and Planetary Interiors*, **161**(1–2), 19–35.

Donadini, F., Kovacheva, M., Kostadinova, M., Hedley, I. G., and Pesonen, L. J., 2008. Palaeointensity determination on an early medieval kiln from Switzerland and the effect of cooling rate. *Physics and Chemistry of the Earth*, **33**(6–7), 449–457.

Donadini, F., Motschi, A., Rösch, C., and Hajdas, I., 2012. Combining an archaeomagnetic and radiocarbon study: dating of medieval fireplaces at the Mühlegasse, Zürich. *Journal of Archaeological Science*, **39**(7), 2153–2166.

Dubois, R. L., and Watanabe, N., 1965. Preliminary results of investigations made to study the use of Indian pottery to determine the paleointensity of the geomagnetic field for the United States 600–1400 A.D. *Journal of Geomagnetism and Geoelectricity*, **17**(3), 417–423.

Eighmy, J. L., 1990. Archaeomagnetic dating: practical problems for the archaeologist. In Eighmy, J. L., and Sternberg, R. S. (eds.), *Archaeomagnetic Dating*. Tucson: The University of Arizona Press, pp. 33–64.

Eighmy, J. L., and Howard, J. B., 1991. Direct dating of prehistoric canal sediments using archaeomagnetism. *American Antiquity*, **56**(1), 88–102.

Eighmy, J. L., and Mitchell, D. R., 1994. Archaeomagnetic dating at Pueblo Grande. *Journal of Archaeological Science*, **21**(4), 445–453.

Eighmy, J. L., and Sternberg, R. S. (eds.), 1990. *Archaeomagnetic Dating*. Tucson: University of Arizona Press.

Finlay, C. C., 2008. Historical variation of the geomagnetic axial dipole. *Physics of the Earth and Planetary Interiors*, **170**(1–2), 1–14.

Fisher, R. A., 1953. Dispersion on a sphere. *Proceedings of the Royal Society of London, Series A*, **217**(1130), 295–305.

Folgheraiter, G., 1899. Sur les variations séculaires de l'inclinaison magnétique dans l'antiquité. *Archives des Sciences Physiques et Naturelles*, **8**, 5–16.

Gilbert, W., 1958. *De Magnete*. New York: Dover: Trans: by Mottelay, P. F., 1893. Originally published 1600.

Goguitchaichvili, A., Greco, C., and Morales, J., 2011. Geomagnetic field intensity behavior in South America between 400 AD and 1800 AD: first archeointensity results from Argentina. *Physics of the Earth and Planetary Interiors*, **186**(3–4), 191–197.

Hagstrum, J. T., and Blinman, E., 2010. Archeomagnetic dating in western North America: an updated reference curve based on paleomagnetic and archeomagnetic data sets. *Geochemistry, Geophysics, Geosystems*, **11**(6), Q06009, doi:10.1029/2009GC002979.

Hagstrum, J. T., and Champion, D. E., 2002. A Holocene paleosecular variation record from ^{14}C-dated volcanic rocks in western North America. *Journal of Geophysical Research, Solid Earth*, **107**(B1), EPM 8–1–EPM 8–14, doi:10.1029/2001JB000524.

Halley, E., 1692. An account of the cause of the change of the variation of the magnetic needle; with an hypothesis of the structure of the internal part of the Earth. *Philosophical Transactions of the Royal Society of London*, **16**(179–191), 563–578.

Henderson, T. K., 2001. Chronology. In Craig, D. B. (ed.), *The Grewe Archaeological Research Project: Vol. 1. Project Background and Feature Descriptions*. Flagstaff: Northland Research. Northland Research Anthropological Papers 99-1, pp. 163–208.

Hueda-Tanabe, Y., Soler-Arechalde, A. M., Urrutia-Fucugauchi, J., Barba, L., Manzanilla, L., Rebolledo-Vieyra, M., and Goguitchaichvili, A., 2004. Archaeomagnetic studies in central Mexico – dating of Mesoamerican lime-plasters. *Physics of the Earth and Planetary Interiors*, **147**(2–3), 269–283.

Hus, J., Geeraerts, R., and Plumier, J., 2004. On the suitability of refractory bricks from a mediaeval brass melting and working site near Dinant (Belgium) as geomagnetic field recorders. *Physics of the Earth and Planetary Interiors*, **147**(2–3), 103–116.

Jackson, A., Jonkers, A. R. T., and Walker, M. R., 2000. Four centuries of geomagnetic secular variation from historical records. *Philosophical Transactions of the Royal Society of London. Series A*, **358**(1768), 957–990.

Jordanova, N., Kovacheva, M., and Kostadinova, M., 2004. Archaeomagnetic investigation and dating of Neolithic archaeological site (Kovachevo) from Bulgaria. *Physics of the Earth and Planetary Interiors*, **147**(2–3), 89–102.

Kirschvink, J. L., 1980. The least-squares line and plane and the analysis of paleomagnetic data. *Geophysical Journal of the Royal Astronomical Society*, **62**(3), 699–718.

Korte, M., Mandea, M., and Matzka, J., 2009. A historical declination curve for Munich from different data sources. *Physics of the Earth and Planetary Interiors*, **177**(3–4), 161–172.

Kostadinova, M., and Kovacheva, M., 2008. Case study of the Bulgarian Neolithic archaeological site of Piperkov Chiflik and its archaeomagnetic dating. *Physics and Chemistry of the Earth, Parts A/B/C*, **33**(6–7), 511–522.

Kovacheva, M., and Toshkov, A., 1994. Geomagnetic field variations as determined from Bulgarian archaeomagnetic data. Part I: the last 2000 years AD. *Surveys in Geophysics*, **15**(6), 673–701.

Kovacheva, M., Jordanova, N., and Karloukovski, V., 1998. Geomagnetic field variations as determined from Bulgarian archaeomagnetic data. Part II: the last 8000 years. *Surveys in Geophysics*, **19**(5), 431–460.

Kovacheva, M., Hedley, I., Jordanova, N., Kostadinova, M., and Gigov, V., 2004. Archaeomagnetic dating of archaeological sites from Switzerland and Bulgaria. *Journal of Archaeological Science*, **31**(10), 1463–1479.

LaBelle, J. M., and Eighmy, J. L., 1997. Additional archaeomagnetic data on the south-west USA master geomagnetic pole curve. *Archaeometry*, **39**(2), 431–439.

Lanos, P., 2004. Bayesian inference of calibration curves: application to archaeomagnetism. In Buck, C. E., and Millard, A. R. (eds.), *Tools for Constructing Chronologies: Crossing Disciplinary Boundaries*. London: Springer. Lecture Notes in Statistics 177, pp. 43–82.

Lanos, P., Le Goff, M., Kovacheva, M., and Schnepp, E., 2005. Hierarchical modelling of archaeomagnetic data and curve estimation by moving average technique. *Geophysical Journal International*, **160**(2), 440–476.

Le Goff, M., and Gallet, Y., 2004. A new three-axis vibrating magnetometer for continuous high-temperature magnetization measurements: applications to paleo- and archaeo-intensity determinations. *Earth and Planetary Science Letters*, **229** (1–2), 31–43.

Le Goff, M., Gallet, Y., Genevey, A., and Warmé, N., 2002. On archeomagnetic secular variation curves and archaeomagnetic dating. *Physics of the Earth and Planetary Interiors*, **134**(3–4), 203–211.

Lengyel, S. N., 2004. *Archaeomagnetic Research in the U.S. Midcontinent*. PhD dissertation, University of Arizona, Tucson. Ann Arbor, University Microfilms.

Lengyel, S. N., 2010. The pre-AD 585 extension of the U.S. Southwest archaeomagnetic reference curve. *Journal of Archaeological Science*, **37**(12), 3081–3090.

Lengyel, S. N., 2011. Chronometric dating and site chronologies. In Wegener, R. M., Heilen, M. P., Ciolek-Torrello, R., and Hall, J. D. (eds.), *The U.S. 60 Archaeological Project: Early Agricultural, Formative, and Historical-Period Use of the Upper Queen Creek Region; Vol. 4. Analyses of Prehistoric Materials in the Queen Valley to Queen Creek Area*. Tucson: Statistical Research. Statistical Research Technical Report 92, pp. 9–51.

Lengyel, S. N., Eighmy, J. L., and Van Buren, M., 2011. Archaeomagnetic research in the Andean highlands. *Journal of Archaeological Science*, **38**(1), 147–155.

Linford, P., 2006. *Archaeomagnetic Dating: Guidelines on Producing and Interpreting Archaeomagnetic Dates*. Portsmouth: English Heritage Publishing.

Linford, P., and Welch, C., 2004. Archaeomagnetic analysis of glassmaking sites at Bagot's Park in Staffordshire, England. *Physics of the Earth and Planetary Interiors*, **147**(2–3), 209–221.

Lodge, A., and Holme, R., 2009. Towards a new approach to archaeomagnetic dating in Europe using geomagnetic field modelling. *Archaeometry*, **51**(2), 309–322.

Melloni, M., 1853. Du magnétisme des roches. *Comptes Rendus de l'Académie Scientifique de Paris*, **37**, 966–968.

Mercanton, P.-L., 1918. État magnétique de quelques terres cuites préhistoriques. *Comptes Rendus des Séances de l'Académie des Sciences de Paris*, **166**, 681–685.

Merrill, R. T., McElhinny, M. W., and McFadden, P. L. (eds.), 1998. *The Magnetic Field of the Earth: Paleomagnetism, the Core, and*

the Deep Mantle. San Diego: Academic. International Geophysics Series 63.
Morales, J., Goguitchaichvili, A., Aguilar-Reyes, B., Pineda-Duran, M., Camps, P., Carvallo, C., and Calvo-Rathert, M., 2011. Are ceramics and bricks reliable absolute geomagnetic intensity carriers? *Physics of the Earth and Planetary Interiors*, **187**(3–4), 310–321.
Nilsson, A., Snowball, I., Muscheler, R., and Uvo, C. B., 2010. Holocene geocentric dipole tilt model constrained by sedimentary paleomagnetic data. *Geochemistry, Geophysics, Geosystems*, **11**(8), Q08018, doi:10.1029/2010GC003118.
Noel, M., and Batt, C. M., 1990. A method for correcting geographically separated remanence directions for the purpose of archaeomagnetic dating. *Geophysical Journal International*, **102**(3), 753–756.
Pavón-Carrasco, F. J., Rodríguez-González, J., Osete, M. L., and Torta, J. M., 2011. A Matlab tool for archaeomagnetic dating. *Journal of Archaeological Science*, **38**(2), 408–419.
Riisager, P., Abrahamsen, N., and Rytter, J., 2003. Research report: magnetic investigations and the age of a medieval kiln at Kungahälla (South-West Sweden). *Archaeometry*, **45**(4), 675–684.
Rimi, A., Tarling, D. H., and El-Alami, S. O., 2004. An archaeomagnetic study of two kilns at Al-Basra. In Benco, N. L. (ed.), *Anatomy of a Medieval Islamic Town: Al-Basra, Morocco*. Oxford: Archaeopress. British Archaeological Reports, International Series 1234, pp. 95–106.
Schnepp, E., and Lanos, P., 2005. Archaeomagnetic secular variation in Germany during the past 2500 years. *Geophysical Journal International*, **163**(2), 479–490.
Schnepp, E., Pucher, R., Reinders, J., Hambach, U., Soffel, H., and Hedley, I., 2004. A German catalogue of archaeomagnetic data. *Geophysical Journal International*, **157**(1), 64–78.
Schnepp, E., Worm, K., and Scholger, R., 2008. Improved sampling techniques for baked clay and soft sediments. *Physics and Chemistry of the Earth, Parts A/B/C*, **33**(6–7), 407–413.
Shaar, R., Ron, H., Tauxe, L., Kessel, R., Agnon, A., Ben-Yosef, E., and Feinberg, J. M., 2010. Testing the accuracy of absolute intensity estimates of the ancient geomagnetic field using copper slag material. *Earth and Planetary Science Letters*, **290**(1–2), 201–213.
Speranza, F., Maritan, L., Mazzoli, C., Morandi Bonacossi, D., and D'Ajello Caracciolo, F., 2006. First directional archaeomagnetic results from Syria: evidence from Tell Mishrifeh/Qatna. *Geophysical Journal International*, **165**(1), 47–52.
Sternberg, R. S., and McGuire, R. H., 1990. Techniques for constructing secular variation curves and for interpreting archaeomagnetic dates. In Eighmy, J. L., and Sternberg, R. S. (eds.), *Archaeomagnetic Dating*. Tucson: University of Arizona Press, pp. 109–134.
Sternberg, R. S., Lange, R. C., Murphy, B. A., Deaver, W. L., and Teague, L. S., 1991. Archaeomagnetic dating at Las Colinas, Arizona, USA. In Pernicka, E., and Wagner, G. A. (eds.), *Archaeometry '90: International Symposium on Archaeometry, 2–6 April 1990, Heidelberg, Germany*. Basel: Birkhäuser Verlag, pp. 597–606.
Tarling, D. H., 1983. *Paleomagnetism: Principles and Applications in Geology, Geophysics and Archaeology*. London: Chapman and Hall.
Tarling, D. H., and Dobson, M. J., 1995. Archaeomagnetism: an error assessment of fired material observations in the British directional database. *Journal of Geomagnetism and Geoelectricity*, **47**(1), 5–18.
Thellier, É., 1936. Détermination de la direction de l'aimantation permanente des roches. *Comptes Rendus Hebdomidaires de l'Académie Scientifique de Paris*, **203**, 743–744.
Thellier, É., 1938. Sur l'aimantation des terres cuites et ses applications géophysiques. *Annales de l'Institut de Physique du Globe de Paris*, **16**, 157–302.
Thellier, É., 1967. Methods of sample collection and orientation for archaeomagnetism. In Collinson, D. W., Creer, K. M., and Runcorn, S. K. (eds.), *Methods in Paleomagnetism: Proceedings of the Nato Advanced Study Institute on Palaeomagnetic Methods, held in the University of Newcastle upon Tyne, April 1–10, 1964*. Amsterdam: Elsevier Publishing Company. Developments in Solid Earth Geophysics 3, pp. 16–20.
Thellier, É., and Thellier, O., 1959. Sur l'intensité du champ magnétique terrestre dans le passé historique et géologique. *Annales de Geophysique*, **15**, 285–376.
Trapanese, A., Batt, C. M., and Schnepp, E., 2008. Sampling methods in archaeomagnetic dating: a comparison using case studies from Wörterberg, Eisenerz and Gams Valley (Austria). *Physics and Chemistry of the Earth, Parts A/B/C*, **33**(6–7), 414–426.
Valet, J.-P., Herrero-Bervera, E., LeMouël, J.-L., and Plenier, G., 2008. Secular variation of the geomagnetic dipole during the past 2000 years. *Geochemistry, Geophysics, Geosystems*, **9**(1), Q01008, doi:10.1029/2007GC001728.
Watanabe, N., 1959. *The Direction of Remanent Magnetism of Baked Earth and Its Application to Chronology for Anthropology and Archaeology in Japan.* Journal of the Faculty of Science, Imperial University of Tokyo. Section 5, Anthropology, 2, Part 1.
Weaver, K. F., 1967. Magnetic clues help date the past. *National Geographic*, **131**(5), 696–701.
Wolfman, D., 1990. Mesoamerican chronology and archaeomagnetic dating, A.D. 1–1200. In Eighmy, J. L., and Sternberg, R. S. (eds.), *Archaeomagnetic Dating*. Tucson: University of Arizona Press, pp. 261–308.
Zananiri, I., Batt, C. M., Lanos, P., Tarling, D. H., and Linford, P., 2007. Archaeomagnetic secular variation in the UK during the past 4000 years and its application to archaeomagnetic dating. *Physics of the Earth and Planetary Interiors*, **160**(2), 97–107.
Zanella, E., Gurioli, L., Chiari, G., Ciarallo, A., Cioni, R., De Carolis, E., and Lanza, R., 2000. Archaeomagnetic results from mural paintings and pyroclastic rocks in Pompeii and Herculaneum. *Physics of the Earth and Planetary Interiors*, **118**(3–4), 227–240.
Zhaoqin, M., and Noel, M., 1989. Archaeomagnetic evidence for the age and duration of firing of mediaeval hearths from Coffee Yard, York. *Geophysical Journal International*, **97**(2), 357–359.

Cross-references

Geophysics
Magnetometry for Archaeology
Paleomagnetism

ARCHAEOMINERALOGY

George Rip Rapp
Department of Geological Sciences, University of Minnesota, Duluth, MN, USA

The term archaeomineralogy is relatively new. It was used by Mitchell (1985) for a brief bibliography, by Rapp (2002, 2009) for books, and by Kostov et al.,

(2008) and Rapp (2008) as part of the first international meeting on archaeomineralogy. This subdiscipline is quite distinct from the history of mineralogy. Archaeomineralogy is a subdiscipline of archaeology or geoarchaeology. It is the study of the exploitation of rocks and minerals by humans since prehistoric times for implements, ornaments, building materials, paints, and as raw material for metals, ceramics, and other processed products. Archaeomineralogy attempts to date, source, and characterize artifacts made from earth materials as well as put this information into geographic and historical contexts.

Scholars who could be called archaeomineralogists go back to ancient times and were located around the globe. Among the most prominent were the Hellenistic Greek philosopher Theophrastus (ca. 372–287 BCE), the Greek physician Dioscorides (ca. 40–90 CE), the Italian Pliny the Elder (ca. 23–79 CE), the Spaniard Isidore of Seville (ca. 560–636 CE), the Arab authors Al-Biruni (973–1048) and Avicenna (980–1037), the Chinese writer Su Song (1070), the Italian Albertus Magnus (ca. 1206–1280), and the German Georgius Agricola (1494–1555); various Sanskrit texts from India mention the use of a wide variety of minerals in medicine (Rapp, 2009).

The early Egyptians had one of the best understandings of mineralogy and lithology in the practice of medicine and the manufacture of monuments and ornaments (Lucas, 1989). Rock names such as basalt, syenite, porphyry, and alabaster have their origins in ancient Egypt. The igneous rock "basalt" appears to have the oldest roots, in use as early as 2000 BCE. The ancient Mesopotamians also had a well-developed understanding of rocks and minerals in industrial uses (Morrey, 1985).

In ancient times color was the most important character to classify rocks and minerals. Colors had significant symbolic attributes (mourning, purity, passion, danger) and minerals and rocks had medicinal and magic properties. Alchemists equated color with the essence or true nature of a substance. Modern understanding of the physical and chemical nature of mineral properties was established only in the early years of the nineteenth century by Joseph-Louis Proust's Law of Constant Composition in 1799 and John Dalton's Atomic Theory in 1805, and the development of accurate methods of chemical analysis.

It should be noted that early rock and mineral identification frequently was haphazard, often relying on color alone. The names given to many mineral species have changed over time and even today some minerals have a variety of names and synonyms (de Fourestier, 1999). Although there are more than a thousand names given to rock lithologies, sorting out what rocks were exploited in antiquity is somewhat easier than for minerals. An excellent guide to rock names is the "Glossary of Geology" (Neuendorf et al., 2005). This glossary presents historical definitions and obsolete variations in names and meanings.

Bibliography

De Fourestier, J., 1999. *Glossary of Mineral Synonyms*. Ontario: The Canadian Mineralogist. Special Publication 2.

Kostov, R., Gaydarska, B., and Gurova, M., (eds), 2008. International Conference on Geoarchaeology and Archaeomineralogy October 2008, Sofia Bulgaria. *Proceedings of the International Conference 29–30 October 2008*. Sofia: Publishing House "st. Ivan Rilski.

Lucas, A., 1989. *Ancient Egyptian Materials and Industries*. Revised by J. Harris. London: Histories and Mysteries of Man Ltd.

Mitchell, R., 1985. *Archaeomineralogy: An Annotated Bibliography of North and Central America (1840–1981)*. Edwardsville: Southern Illinois University.

Morrey, P.R., 1985, *Materials and Manufacture in Ancient Mesopotamia: the Evidence of Archaeology and Art. Metals and Metalwork, Glazed Materials and Glass*. Oxford: British Archaeological Reports, International Series 237.

Neuendorf, K., Mehl, J., and Jackson, J. (eds.), 2005. *Glossary of Geology*, 5th edn. Alexandra, VA: American Geological Institute.

Rapp, G. R., 2002. *Archaeomineralogy*. Berlin: Springer.

Rapp, G. R., 2008. *Should Archaeomineralogy Now Follow Geoarchaeology into the Family of Organized Scholarly Fields?* pp. 13–14 in Kostov et al. 2008.

Rapp, G. R., 2009. *Archaeomineralogy*, 2nd edn. Berlin: Springer.

Cross-references

Lithics
Pigments

ARCHAEOSEISMOLOGY

Tina M. Niemi
Department of Geosciences, University of Missouri-Kansas City, Kansas City, MO, USA

Synonyms

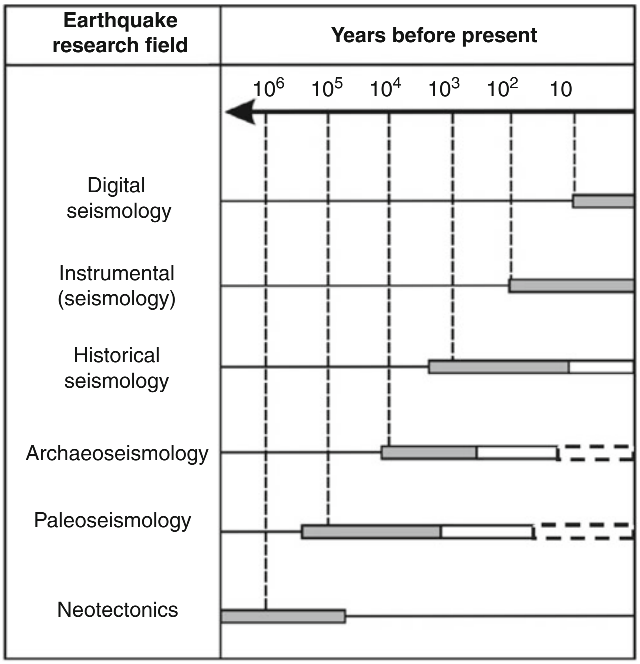
Earthquake archaeology; Seismic archaeology

Definition

The study of ancient earthquakes at archaeological sites.

Introduction

Earthquakes have disrupted human societies throughout history and prehistory. Whereas hunter-gatherer cultures may have been relatively little affected by seismic events, the built environment of sedentary societies can be quite vulnerable to collapse of structures by earthquake-induced ground motion. Understanding the severity and frequency of past earthquakes is important for understanding the history, consequences, and responses of past societies to these seismic disasters, as well as the hazards posed to modern populations. In many parts of the world, the recurrence of earthquakes is so infrequent that modern instrumental seismic data do not adequately represent the



Archaeoseismology, Figure 1 The study of instrumentally recorded earthquakes is the field of seismology. Pre-instrumental earthquakes are studied by other methods, including historical seismology that encompasses written history, archaeoseismology that documents earthquakes at archaeological sites, and the geologic studies of paleoseismology and neotectonics (Modified after Caputo and Helly, 2008).

earthquake potential. Therefore, other methods to document the history of earthquakes are needed.

Various sources of data provide evidence of earthquake occurrence and magnitude, albeit at varying resolutions and over different time scales. Seismology, or the study of earthquake data recorded on analog seismographs, and now digital seismometers, is a field that has documented the date, time, and other parameters of seismic events over the past century or so. Information on earthquakes prior to the late nineteenth century relies on other research fields, including historical seismology, archaeoseismology, paleoseismology, and neotectonics (Figure 1). The figure clearly shows that the time domain for each field of earthquake study overlaps, often significantly. In historical seismology, the record of written history varies across geographic regions, and only a few cultures in the Near and Far East have produced written accounts of earthquakes that extend as far back as two to four millennia. Furthermore, historical texts become increasingly incomplete with increasing antiquity, as well as in regions of sparse population or discontinuous habitation. In many areas, historical records are completely absent. The physical remains of complex societies extend thousands of years farther back in time, well beyond the earliest historical accounts, and they are distributed more widely over the globe. Thus, the evidence of earthquakes at archaeological sites revealed by archaeoseismology may potentially fill a much-needed void in the record of seismic events. Geologists have also studied faults, deformation, and ground rupture from modern, historical, and ancient earthquakes within the well-established fields of paleoseismology and neotectonics.

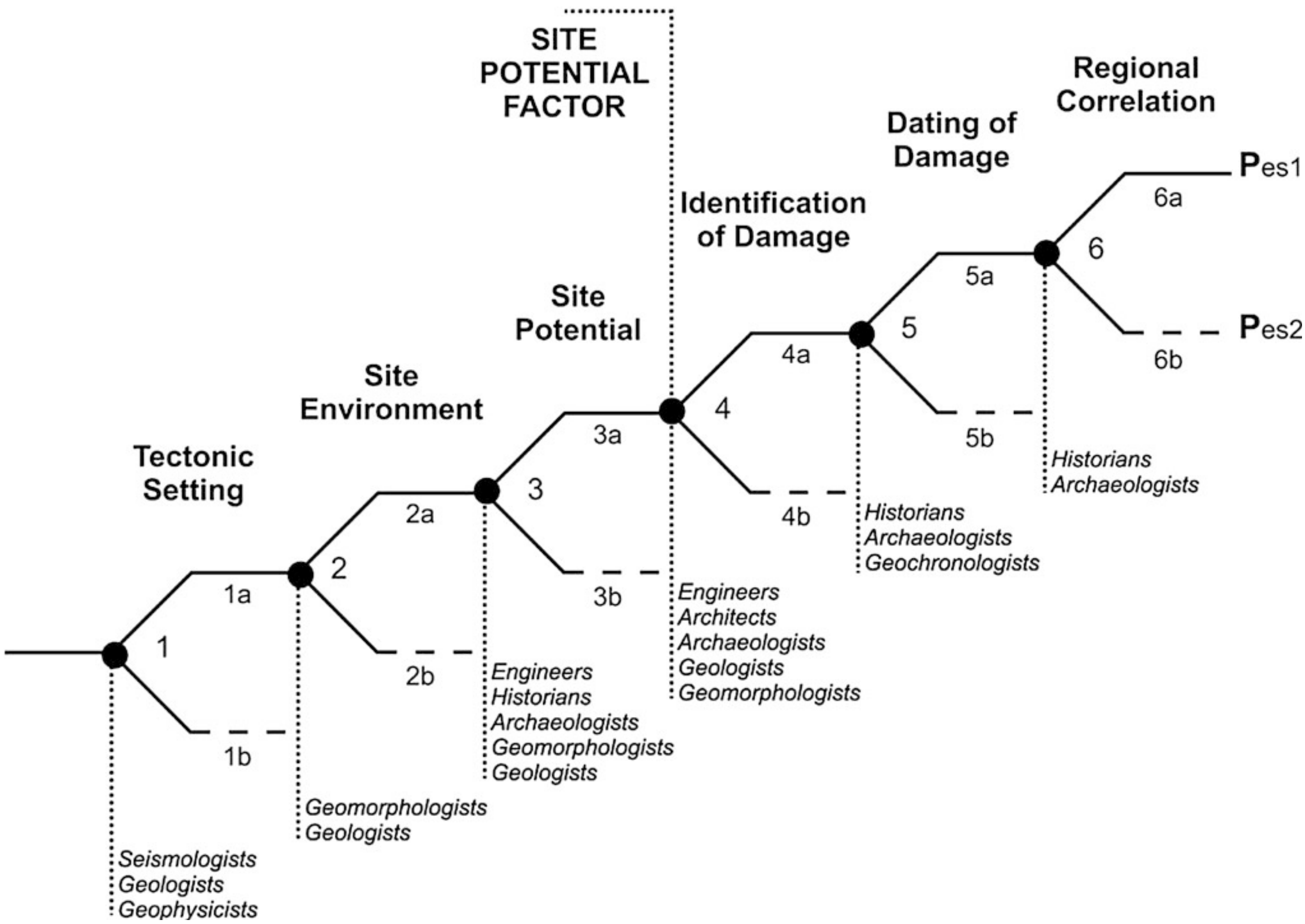
History of the field of archaeoseismology

Ambraseys (1971, 1973) was one of the first to advocate the modern use of archaeological data to help define a region's earthquake history and other seismic hazards. Deciphering and dating evidence of earthquake damage at archaeological sites is the goal of the modern field of "archaeoseismology" – a term first coined in the paper by Karcz and Kafri (1978). Several other terms have been used for this emerging field, including "seismic archaeology" (e.g., Guidoboni, 1996) and "earthquake archaeology" (e.g., Sbeinati et al., 2010).

Many archaeologists have documented "destruction horizons," i.e., stratigraphic layers that show signs of fire, instantaneous destruction, or massive structural collapse with evidence of smashed, in situ vessels on living surfaces, toppled masonry, or other catastrophic building failures. These destruction horizons have been interpreted as evidence for ancient earthquakes since the late 1890s and early 1900s, when large-scale excavations of sites across the Mediterranean and Near East were launched (e.g., Arthur Evans's excavations of the Minoan palace at Knossos on Crete). While outlining the clear benefits of archaeological data in earthquake research, Ambraseys (1971, 1973) also cautioned that modern structures respond differently from ancient buildings to ground shaking. Because some ancient structures are still standing, it should not be concluded that the hazard of future earthquakes is low. Further, he observed that earthquakes should not be indiscriminately used to explain a sudden abandonment or large changes in cultural history.

The field of archaeoseismology investigates both earthquake collapse horizons within archaeological stratigraphic contexts and damaged extant buildings and structures. Earthquake damage is, however, difficult to differentiate from other causes of building failures, including static collapse due to lack of maintenance and disrepair, slumping or gravitational sliding, foundation subsidence, and other geotechnical issues (e.g., Karcz and Kafri, 1978; Rapp, 1986; Stiros and Jones, 1996; Galadini et al., 2006; Marco, 2008). Buildings and monuments damaged in an ancient earthquake may also show signs of repair. But again, many authors have noted that reconstruction phases may relate to expansion due to population growth repairs after military conflict, or political, social, or religious reorganization (e.g., Guidoboni and Ebel, 2009), and they cannot be strictly interpreted as evidence for an earthquake.

Archaeological excavations have traditionally concentrated on monumental structures and cities. Therefore,



Archaeoseismology, Figure 2 Archaeoseismic quality factor (AQF) is a two-branch logic tree that can be utilized to evaluate whether an archaeological site is favorably located to record earthquake damage (site potential factor) and the extent to which features can be used as evidence for an earthquake based on the type of damage, its dating, and regional distribution (After Sintubin and Stewart, 2008).

the so-called hinterland or rural, agricultural villages and farmsteads have not received as much attention. The advent of survey archaeology, which systematically records sites and artifacts across the landscape, allows estimation of settlement patterns and population trends during different sequential periods of occupation. Guidoboni et al. (2000) analyzed the archaeological data around the area of southern Italy and Sicily that was affected by the 1908 M7 earthquake in the Strait of Messina; they concluded that evidence of earthquakes can be identified based on changes in habitation patterns. From the archaeological survey data, in conjunction with epigraphic, archaeological collapse horizons, reuse of inscribed blocks, and potential tsunami deposits, they suggest that contraction of settlements was a response to a large damaging earthquake circa 350–363 CE. Guidoboni et al. (2000, 45) call this method "territorial archaeoseismology."

Several papers have highlighted how earthquakes at archaeological sites, if not independently dated through artifactual or numismatic means, can lead to circular reasoning (e.g., Ambraseys, 2005, 2006; Rucker and Niemi, 2010). In such cases, historical earthquake catalogs are used to assign dates to archaeological collapse horizons, and then the evidence of collapse from the archaeological site is entered into the earthquake catalog as evidence for a particular seismic event. Because earthquake catalogs are inherently incomplete, this practice can lead to amalgamation and distortion of seismic event dates and locations. As is clear across all subdisciplines of geoarchaeology, interpretive problems can be avoided largely through direct field collaboration between archaeologists and earth scientists within an interdisciplinary or multidisciplinary approach to research (e.g., Guidoboni, 1996; Ambraseys, 2006).

Understanding the tectonic, geologic, and geomorphic setting of an archaeological site has long been recognized as fundamental to understanding archaeoseismic evidence (e.g., Karcz and Kafri, 1978; Rapp, 1986). Sintubin and Stewart (2008) proposed a two-branch logic tree that can

Archaeoseismology, Figure 3 (Continued) be utilized to evaluate whether an archaeological site is favorably located to record earthquake damage (site potential factor) and the extent to which features can be used as evidence for an earthquake based on the type of damage, its dating, and regional distribution (Figure 2). These authors introduce an archaeoseismic quality factor (AQF) as a numerical means to evaluate confidence levels for the archaeoseismic data. The AQF has been applied to a couple of sites, including Sagalassos in southwestern Turkey (Sintubin and Stewart, 2008) and Baelo Claudia in southern Spain (Grützner et al., 2010).

Archaeological evidence of past earthquakes

Earthquake damage to structures

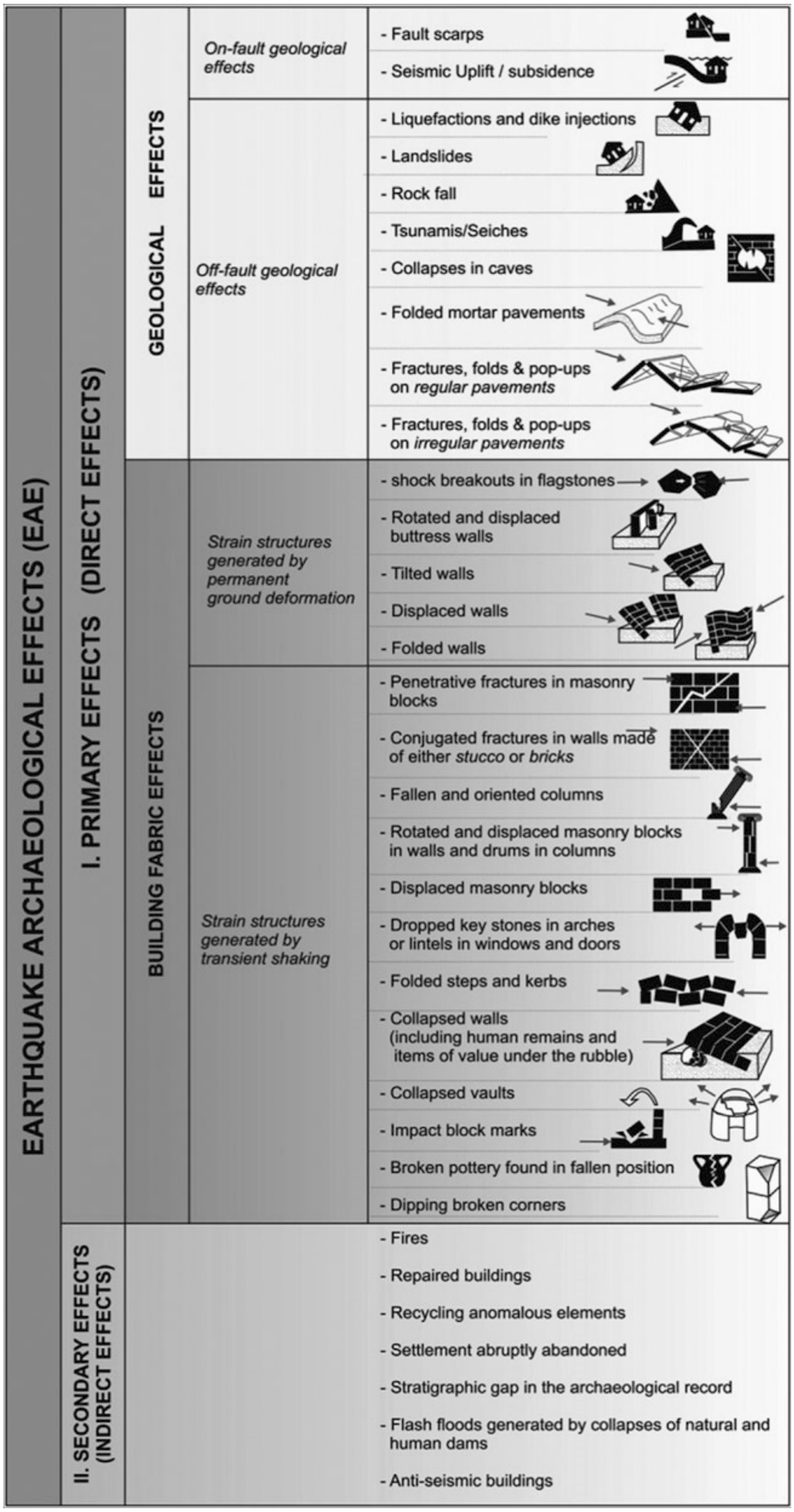
Stiros (1996) provided one of the first published lists of criteria to identify earthquake damage at an archaeological site. Buildings of blocks (brick or stone) and mortar behave differently from a building of large dimensional stones set on top of each other (dry masonry). Buildings of mudbrick or wood framing also have a specific response to seismic shaking. Much of what has been developed in archaeoseismology has focused on the Mediterranean region. Characteristic seismic damages to structures, here summarized from Stiros (1996), Galadini et al. (2006), and Hinzen (2009), include: (1) cross fissures in the vertical plane due to shear forces and diagonal cracks in rigid walls; (2) triangular corner expulsion due to orthogonal motion of walls; (3) lateral and rotational horizontal and independent motion of blocks within a wall, seen as open vertical fractures; (4) height reduction due to vertical crashing; (5) deformation of arch piers including collapse of keystones; (6) wall tilting and distortion; (7) rotation or toppling of pillars and column drums often aligned in a row or laid out "domino style"; and (8) impact of architectural elements on pavement. Photographic examples of these features are shown in Figure 3.

Scientific inquiry into the fall direction of monuments, statues, and structures largely began with Robert Mallet's (1862) investigation of the 1857 Naples earthquake in Italy. Numerous investigators have postulated that the fall direction of building columns or column drums and other architectural elements of a building has azimuthal relevance with respect to the causal earthquake. It should be evident, though not always acknowledged, that freestanding columns or monuments, such as an obelisk, will respond differently from a line of columns supporting a structure, such as a temple or church. A column that is carrying a load, like the superstructure of a building, is not free to fall in any direction. Numerical modeling of a single standing column using "input motion from 29 - strong-motion records indicates little correlation between downfall directions and back azimuth" (Hinzen, 2009, 2855). This study showed that, although columns often fall in a parallel alignment, the data cannot be used to determine the direction to the earthquake epicenter.

A variety of scales have been developed to quantify the intensity of ground shaking and the effects of an earthquake on people and animals, as well as damage to the built environment (e.g., the modified Mercalli scale). To measure earthquake intensity from seismically induced ground features recorded in the natural environment, the International Union for Quaternary Research (INQUA) developed the environmental seismic intensity (ESI) scale (Michetti et al., 2007). More recently, Rodríguez-Pascua et al. (2011) proposed an earthquake intensity scale for seismic damage at archaeological sites called the Earthquake Archaeological Effects (EAE), which is modeled after the ESI scale (Figure 4). The EAE scale divides earthquake damage into two categories: (1) those events affecting building fabric, either from seismic shaking of the superstructure or strain on the foundation, and (2) geologic effects on ancient buildings caused by faulting or other seismically induced ground failures. It is clear, however, that many of the features in the EAE scale (e.g., tilted or displaced walls, deformed or fractured pavement, cave or other structural collapses, among others) can occur under natural soil movement and gravitational conditions without invoking seismic excitation. Therefore, identification of one or two features in the EAE scale should not be interpreted as evidence for an earthquake without assessing the geological conditions of the site or performing something equivalent to the AQF test.

Quantification of earthquake damage at archaeological sites is complicated, as the conditions of the building before and after the earthquake in antiquity are not known. Extant buildings may have also experienced ground motion from multiple earthquakes originating from different source areas. Stiros (1996) cautions that recognition of earthquake damage can be assured only if other mechanisms of deformation such as differential ground subsidence, gravitational ground failures (i.e., slumps, landslides, rockfalls, etc.), shrinking and swelling soils, or poor construction, among other natural and structural engineering issues related to building collapse and failure, can be eliminated. Many fractures, warps, and collapses cannot unequivocally be designated as damage from an earthquake.

Archaeoseismology, Figure 3 Evidence of earthquakes at various archaeological sites: (**a**) destruction horizon at the Chalcolithic site of Hujereit al Ghuzlan in Aqaba, Jordan; (**b**) fallen columns at Petra, Jordan; (**c**) shifted keystone at the Crac des Chevaliers Crusader castle in Syria; (**d**) rotated, horizontally shifted blocks of gypsum at the Roman fortified city of Dura-Europos in Syria – in this case, the deformation is caused by military undermining of the wall during the siege of the city; (**e**) the collapsed wall of the city gate at Hierapolis, Turkey; (**f**) fracture crossing a stepped cistern at the Qumran site in Israel – the fracture is likely due to unstable lake marls beneath the reservoir rather than a through-going fault; and (**g**) impacted pavement at the Magnesia site, Turkey.



Archaeoseismology, Figure 4 The Earthquake Archaeology Effects seismic intensity scale divides earthquake damage into events affecting the building fabric, either from seismic shaking of the superstructure or strain on the foundation, or those geologic effects on ancient buildings caused by faulting or other seismically induced ground failures (After Rodríguez-Pascua et al., 2011).

Several studies have used detailed mapping of damage to extant archaeological structures to calculate ground motion that created the structural failures. Hinzen (2005) modeled the natural reactions of the soil under conditions of a local source earthquake and the resultant displacement to an ancient construction. He concluded that an earthquake caused the wall cracks, displacements, and rotations in the Roman fortifications at the Tolbiacum site in Germany. Kamai and Hatzor (2008) used the discontinuous deformation analysis method to calculate the peak ground acceleration that produced slipped keystones of arches at the Mamshit and Nimrod Fortress archaeological sites in Israel. These methods hold promise for quantifying earthquake parameters from archaeological data.

Coseismic offset at archaeological sites

One of the ways archaeological data can be used to quantify a seismic source is to define the amount of fault slip from a past earthquake (i.e., coseismic slip). Based on modern empirical relationships between earthquake magnitude and fault slip (e.g., Wells and Coppersmith, 1994), matching features that were offset across a fault, whether they are natural geologic (such as a riverbed) or cultural (such as a wall), can lead to estimation of the magnitude of an ancient earthquake. The advantage of utilizing archaeological piercing points (points that can be matched across a fault that have been displaced by an earthquake) is that they can often be more precisely dated than geologic deposits. The type of fault offset expected at an archaeological site depends on its tectonic setting. Thus, any number of deformations can be expected including strike slip (horizontal displacement), dip slip (vertical displacement), or oblique slip (both horizontal and vertical displacement), and land level changes due to tectonic uplift, subsidence, or folding. Offset archaeological data were summarized in Noller (2001), although additional work has clearly been conducted since his compilation.

The isolated observation of a single offset architectural feature from an archaeological site is not sufficient to differentiate between coseismic faulting and other shear plane failures, such as landslides. Landslide scarps, tensional fractures, and other features due to gravitational sliding can also produce offsets at an archaeological site. It is necessary to map the areal extent of fractures or offsets in order to interpret whether they represent an arcuate landslide scarp or a through-going fault rupture. Aseismic differential settling of a structure can also produce features that appear like fault offsets (e.g., Karcz and Kafri, 1978). Therefore, the interpretation of offset strata or structures at an archaeological site needs to be evaluated within the context of geologic and geomorphic site characterization.

Strike-slip faults laterally offset features either in a right- or left-shear sense across the fault or in a combined oblique slip. Perhaps one of the earliest and most spectacular documentations of offset is the three-meter right-lateral and two-meter horizontal displacement of the Great Wall of China in the 1739 earthquake (Zhang et al., 1986). A number of studies have documented strike-slip offset of ancient architectural features across the Dead Sea Transform (Figure 5). These include the fortification wall of the Crusader castle of Vadum Jacob (Ateret fortress) in northern Israel (Marco et al., 1997), the aqueduct and reservoir at Byzantine Qasr Tilah in Jordan in Figure 5a (Haynes et al., 2006), Neolithic tell and Roman road near Antakya, Turkey (Altunel et al., 2009), and the Al Harif Roman aqueduct in Syria (Meghraoui et al., 2003; Sbeinati et al., 2010). The last study clearly shows that after the first two fault ruptures, the aqueduct was repaired preserving a left-lateral bend. Archaeological sites that lack architecture can also be used to measure coseismic slip as is exemplified in the displacement of Native American middens along the San Andreas fault system in California (Noller and Lightfoot, 1997; Noller, 2001).

Extensional tectonic areas (regions where the continent is being stretched) are characterized by normal faults with steep triangular-faceted mountain fronts adjacent to linear valleys. Because of the abundance of normal faulting in Greece, western Turkey, and Italy and the extensive Bronze Age through Classical period archaeological excavations, many archaeoseismologic studies describing earthquake damage have been published from this region. However, few studies document direct normal-fault slip of archaeological remains, but rather show activity of normal faults adjacent to a site, as in the study of the Helike fault in Greece (Koukouvelas et al., 2001). The Helike fault study also suggested regional Gulf of Corinth tectonic subsidence to partially explain the burial of the Helike archaeological site. Hancock and Altunel (1997) report offset walls and water channels from the Roman to late Byzantine period at the site of Hierapolis in Turkey. Other examples of normal fault offset include a 4-m offset of a Roman aqueduct in southern Italy (Galli et al., 2010) and small offsets in Sicily (Barreca et al., 2010).

Tectonic geomorphological studies in convergent tectonic regions show that surface deformation in a compressive earthquake is complex. Depending on the specifics of the tectonic setting and the location of the archaeological site, an earthquake can produce fault rupture, or surface subsidence or uplift. Harbor sites are particularly good in recording deformation because sea level provides a datum for land level changes. The site of Phalasarna in western Crete was identified as early as the 1850s as an uplifted ancient harbor (Figure 5). Stefanakis (2010) summarizes the extensive research conducted into the great subduction zone earthquake of 365 CE that produced about eight to nine meters of coseismic uplift, leaving the ports of Phalasarna and Kissamos isolated. This earthquake also caused a devastating tsunami that crossed the eastern Mediterranean. Identification of tsunamis in archaeological context is discussed elsewhere in this book.

Archaeoseismology, Figure 5 An archaeological site that is located directly over an active fault may record offset of an architectural feature or other anthropogenic layer in an earthquake, including: (**a**) offset of the Al Harif Roman aqueduct in Syria, (**b**) offset of the aqueduct by about 2 m at the Qasr Tilah site in Jordan (Haynes et al., 2006), (**c**) the ancient harbor of Phalasarna in Western Crete was uplifted more than 8 m in the earthquake of 365 CE (e.g., Stefanakis, 2010), and (**d**) detail of the port boat ties.

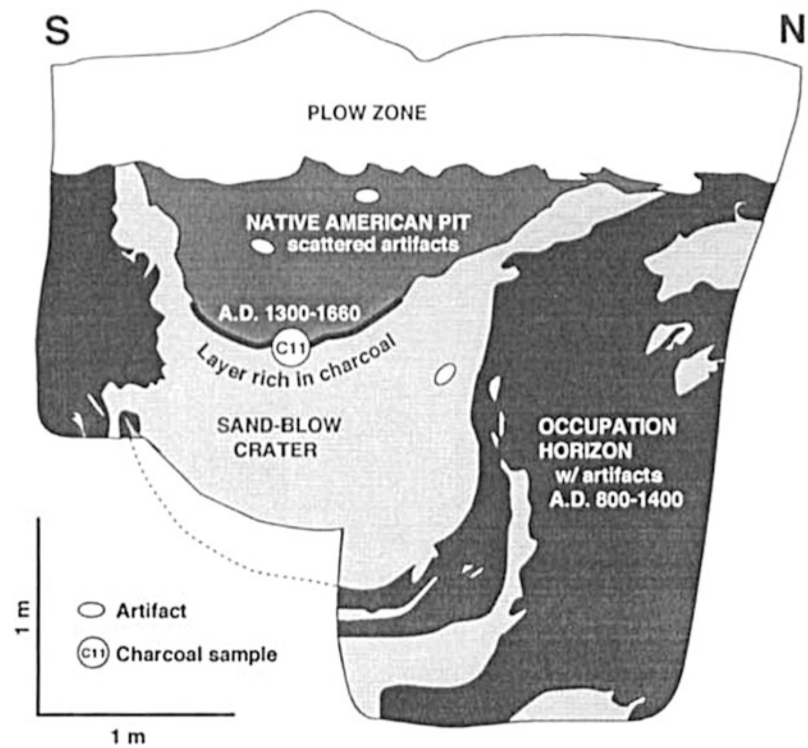
Liquefaction

In many areas of the world, the archaeological record does not include an abundance of monumental stone buildings. Consequently, methods to decipher earthquakes in the Mediterranean do not necessarily transfer readily to other regions of the world. In areas where the predominant building style is post and wall construction with organic materials, as is typical in many seminomadic cultures, or where building traditions preclude heavy masonry because of building tradition or lack of suitable resources, other methods of describing earthquake damage need to be devised. One successful method to document earthquakes in these regions is mapping and dating liquefaction features within archaeological sites.

Liquefaction occurs when shallow, saturated, loose sand loses strength and flows due to cyclical loading of seismic waves. Several features are diagnostic of liquefaction, including fluidized sedimentary structures, sand dikes, sand sills, sand blows and craters, land subsidence, and lateral movement (spread) of surface sediment toward topographically low areas. Native American occupation sites and artifacts buried or deformed by liquefaction (Figure 6) have been extensively used to date paleoearthquakes in the New Madrid seismic zone in the stable craton (interior) of North America (e.g., Tuttle et al., 1996, 2011). Other pioneering work utilizing liquefaction features to date earthquakes at archaeological sites has been conducted in Japan. Barnes (2010) provides a comprehensive summary of the Japanese archaeoseismologic studies.

Summary

The field of archaeoseismology developed out of dual needs: (1) to verify the historical record of earthquakes at sites and (2) to document earthquakes that are silent in the historical accounts but may have played a pivotal role in local and regional cultural history. Damage from earthquakes at archaeological sites has been widely observed in stratigraphic destruction horizons and in damaged architectural features and buildings. Cracks, fissures, tilted, distorted, and displaced walls, columns, floors, and pavements, slipped keystones, collapsed but aligned columns and walls, subsidence, slides, warping, and other deformations of the architectural elements of buildings and other



Archaeoseismology, Figure 6 Liquefaction features from the New Madrid seismic zone of the Central United States showing a sandblow crater formed in an earthquake that buries and deforms the lower occupation layer. Younger Native American deposits are found on top of the sandblow feature (After Tuttle et al., 1996).

structures have been cited as evidence of earthquake damage. This type of data cannot be interpreted as seismically induced until other causes have been eliminated.

In addition to dates of past earthquakes, archaeoseismic methods can provide either a measure of the amount of coseismic slip or the intensity of ground motion, both of which can be used to estimate the magnitude and epicenter of a paleoearthquake. In areas with a tradition of predominantly timber construction, the typical physical evidence of earthquake damage may be liquefaction. Working directly with the archaeologist in the field through an interdisciplinary approach or using unpublished original plans, maps, section drawings, and field notes is preferable to relying on published archaeological summaries. Archaeoseismology is a new and developing field that is evolving from its early focus on qualitative observations to more recent measurement of quantitative data to learn about past earthquakes.

Bibliography

Altunel, E., Meghraoui, M., Karabacak, V., Akyüz, S. H., Ferry, M., Yalçıner, Ç., and Munschy, M., 2009. Archaeological sites (tell and road) offset by the Dead Sea Fault in the Amik Basin, Southern Turkey. *Geophysical Journal International*, **179**(3), 1313–1329.

Ambraseys, N. N., 1971. Value of historical records of earthquakes. *Nature*, **232**(5310), 375–379.

Ambraseys, N. N., 1973. Earth sciences in archaeology and history. *Antiquity*, **47**(187), 229–230.

Ambraseys, N. N., 2005. Archaeoseismology and neocatastrophism. *Seismological Research Letters*, **76**(5), 560–564.

Ambraseys, N. N., 2006. Earthquakes and archaeology. *Journal of Archaeological Science*, **33**(7), 1008–1016.

Barnes, G. L., 2010. Earthquake archaeology in Japan: an overview. In Sintubin, M., Stewart, I. S., Niemi, T. M., and Altunel, E. (eds.), *Ancient Earthquakes*. Boulder, CO: Geological Society of America, pp. 81–96. Geological Society of America special paper, 471.

Barreca, G., Barbano, M. S., Carbone, S., and Monaco, C., 2010. Archaeological evidence for Roman-age faulting in central-northern Sicily: possible effects of coseismic deformation. In Sintubin, M., Stewart, I. S., Niemi, T. M., and Altunel, E. (eds.), *Ancient Earthquakes*. Boulder, CO: Geological Society of America, pp. 223–232. Geological Society of America special paper, 471.

Caputo, R., and Helly, B., 2008. The use of distinct disciplines to investigate past earthquakes. *Tectonophysics*, **453**(1–4), 7–19.

Galadini, F., Hinzen, K.-G., and Stiros, S., 2006. Archaeoseismology: methodological issues and procedure. *Journal of Seismology*, **10**(4), 395–414.

Galli, P. A. C., Giocoli, A., Naso, J. A., Piscitelli, S., Rizzo, E., Capini, S., and Scaroina, L., 2010. Faulting of the Roman aqueduct of Venafrum (southern Italy): methods of investigation, results, and seismotectonic implications. In Sintubin, M., Stewart, I. S., Niemi, T. M., and Altunel, E. (eds.), *Ancient Earthquakes*. Boulder, CO: Geological Society of America, pp. 233–242. Geological Society of America special paper, 471.

Grützner, C., Reicherter, K., and Silva, P. G., 2010. Comparing semi-quantitative logic trees for archaeoseismology and paleoseismology: the Baelo Claudia (southern Spain) case study. In Sintubin, M., Stewart, I. S., Niemi, T. M., and Altunel, E. (eds.), *Ancient Earthquakes*. Boulder, CO: Geological Society of America, pp. 129–143. Geological Society of America special paper, 471.

Guidoboni, E., 1996. Archaeology and historical seismology: the need for collaboration in the Mediterranean area. In Stiros, S. C., and Jones, R. E. (eds.), *Archaeoseismology*. Athens: Institute of Geology and Mineral Exploration/British School at Athens, pp. 7–13. Fitch Laboratory occasional paper, 7.

Guidoboni, E., and Ebel, J. E., 2009. *Earthquakes and Tsunamis in the Past: A Guide to Techniques in Historical Seismology*. Cambridge: Cambridge University Press.

Guidoboni, E., Muggia, A., and Valensise, G., 2000. Aims and methods in territorial archaeology: possible clues to a strong fourth-century AD earthquake in the Straits of Messina (southern Italy). In McGuire, W. J., Griffiths, D. R., Hancock, P. L., and Stewart, I. S. (eds.), *The Archaeology of Geological Catastrophes*. London: The Geological Society of London, pp. 45–70. Special publication, 171.

Hancock, P. L., and Altunel, E., 1997. Faulted archaeological relics at Hierapolis (Pamukkale), Turkey. *Journal of Geodynamics*, **24** (1–4), 21–36.

Haynes, J. M., Niemi, T. M., and Atallah, M., 2006. Evidence for ground-rupturing earthquakes on the Northern Wadi Araba fault at the archaeological site of Qasr Tilah, Dead Sea transform fault system, Jordan. *Journal of Seismology*, **10**(4), 415–430.

Hinzen, K.-G., 2005. The use of engineering seismological models to interpret archaeoseismological findings in Tolbiacum, Germany: a case study. *Bulletin of the Seismological Society of America*, **95**(2), 521–539.

Hinzen, K.-G., 2009. Simulation of toppling columns in archaeoseismology. *Bulletin of the Seismological Society of America*, **99**(5), 2855–2875.

Kamai, R., and Hatzor, Y. H., 2008. Numerical analysis of block stone displacements in ancient masonry structures: a new method to estimate historic ground motions. *International Journal for Numerical and Analytical Methods in Geomechanics*, **32**(11), 1321–1340.

Karcz, I., and Kafri, U., 1978. Evaluation of supposed archaeoseismic damage in Israel. *Journal of Archaeological Science*, **5**(3), 237–253.

Koukouvelas, I. K., Stamatopoulos, L., Katsonopoulou, D., and Pavlides, S., 2001. A palaeoseismological and geoarchaeological investigation of the Eliki fault, Gulf of Corinth, Greece. *Journal of Structural Geology*, **23**(2–3), 531–543.

Mallet, R., 1862. *Great Neapolitanian Earthquake of 1857. The First Principles of Observational Seismology as Developed in the Report to the Royal Society of London of the Expedition made by Command of the Society into the Interior of the Kingdom of Naples, to Investigate the Circumstances of the Great Earthquake of December 1857*. London: Chapman and Hall, Vol. II.

Marco, S., 2008. Recognition of earthquake-related damage in archaeological sites: examples from the Dead Sea fault zone. *Tectonophysics*, **453**(1–4), 148–156.

Marco, S., Agnon, A., Ellenblum, R., Eidelman, A., Basson, U., and Boas, A., 1997. 817-year-old walls offset sinistrally 2.1 m by the Dead Sea Transform, Israel. *Journal of Geodynamics*, **24**(1–4), 11–20.

Meghraoui, M., Gomez, F., Sbeinati, R., Van der Woerd, J., Mouty, M., Darkal, A. N., Radwan, Y., Layyous, I., Al Najjar, H., Darawcheh, R., Hijazi, F., Al-Ghazzi, R., and Barazangi, M., 2003. Evidence for 830 years of seismic quiescence from palaeoseismology, archaeoseismology and historical seismicity along the Dead Sea fault in Syria. *Earth and Planetary Science Letters*, **210**(1–2), 35–52.

Michetti, A. M., Esposito, E., Guerrieri, L., Porfido, S., Serva, L., Tatevossian, R., Vittori, E., Audemard, F., Azuma, T., Clague, J., Comerci, V., Gürpinar, A., McCalpin, J., Mohammadioun, B., Mörner, N. A., Ota, Y., and Roghozin, E., 2007. Intensity Scale ESI 2007. In Guerrieri, L., and Vittori, E. (eds.), *Memorie Descrittive della Carta Geologica d'Italia, 74*. Rome: Servizio Geologico d'Italia–Dipartimento Difesa del Suolo, APAT.

Noller, J. S., 2001. Archaeoseismology: shaking out the history of humans and earthquakes. In Goldberg, P., Holliday, V. T., and Ferring, C. R. (eds.), *Earth Sciences and Archaeology*. New York: Kluwer Academic/Plenum Publishers, pp. 143–170.

Noller, J. S., and Lightfoot, K. G., 1997. An archaeoseismic approach and method for the study of active strike-slip faults. *Geoarchaeology*, **12**(2), 117–135.

Rapp, G., Jr., 1986. Assessing archaeological evidence for seismic catastrophes. *Geoarchaeology*, **1**(4), 365–379.

Rodríguez-Pascua, M. A., Pérez-López, R., Giner-Robles, J. L., Silva, P. G., Garduño-Monroy, V. H., and Reicherter, K., 2011. A comprehensive classification of Earthquake Archaeological Effects (EAE) in archaeoseismology: application to ancient remains of Roman and Mesoamerican cultures. *Quaternary International*, **242**(1), 20–30.

Rucker, J. D., and Niemi, T. M., 2010. Historical earthquake catalogues and archaeological data: achieving synthesis without circular reasoning. In Sintubin, M., Stewart, I. S., Niemi, T. M., and Altunel, E. (eds.), *Ancient Earthquakes*. Boulder, CO: Geological Society of America, pp. 97–106. Geological Society of America special paper, 471.

Sbeinati, M. R., Meghraoui, M., Suleyman, G., Gomez, F., Grootes, P., Nadeau, M.-J., Al Najjar, H., and Al-Ghazzi, R., 2010. Timing of earthquake ruptures at the Al Harif Roman aqueduct (Dead Sea fault, Syria) from archaeoseismology and paleoseismology. In Sintubin, M., Stewart, I. S., Niemi, T. M., and Altunel, E. (eds.), *Ancient Earthquakes*. Boulder, CO: Geological Society of America, pp. 243–267. Geological Society of America special paper, 471.

Sintubin, M., and Stewart, I. S., 2008. A logical methodology for archaeoseismology: a proof of concept at the archaeological site of Sagalassos, southwest Turkey. *Bulletin of the Seismological Society of America*, **98**(5), 2209–2230.

Sintubin, M., Stewart, I. S., Niemi, T. M., and Altunel, E. (eds.), 2010. *Ancient Earthquakes*. Boulder, CO: Geological Society of America. Geological Society of America special paper, 471.

Stefanakis, M. I., 2010. Western Crete: from Captain Spratt to modern archaeoseismology, 2010. In Sintubin, M., Stewart, I. S., Niemi, T. M., and Altunel, E. (eds.), *Ancient Earthquakes*. Boulder, CO: Geological Society of America, pp. 67–79. Geological Society of America special paper, 471.

Stiros, S. C., 1996. Identification of earthquakes from archaeological data: methodology, criteria and limitations. In Stiros, S. C., and Jones, R. E. (eds.), *Archaeoseismology*. Athens: Institute of Geology and Mineral Exploration/British School at Athens, pp. 129–152. Fitch Laboratory occasional paper, 7.

Stiros, S. C., and Jones, R. E., 1996. *Archaeoseismology*. Athens: Institute of Geology and Mineral Exploration/British School at Athens. Fitch Laboratory occasional paper, 7.

Tuttle, M. P., Lafferty, R. H., III, Guccione, M. J., Schweig, E. S., Lopinot, N., Cande, R. F., Dyer-Williams, K., and Haynes, M., 1996. Use of archaeology to date liquefaction features and seismic events in the New Madrid seismic zone, central United States. *Geoarchaeology*, **11**(6), 451–480.

Tuttle, M. P., Lafferty, R. H., III, Cande, R. F., and Sierzchula, M. C., 2011. Impact of earthquake-induced liquefaction and related ground failure on a Mississippian archeological site in the New Madrid seismic zone, central USA. *Quaternary International*, **242**(1), 126–137.

Wells, D. L., and Coppersmith, K. J., 1994. New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement. *Bulletin of the Seismological Society of America*, **84**(4), 974–1002.

Zhang, B., Liao, Y., Guo, S., Wallace, R. E., Bucknam, R. C., and Hanks, T. C., 1986. Fault scarps related to the 1739 earthquake and seismicity of the Yinchuan graben, Ningxia Huizu Zizhiqu, China. *Bulletin of the Seismological Society of America*, **76**(5), 1253–1287.

ARCTIC GEOARCHAEOLOGY: SITE FORMATION PROCESSES

Kelly E. Graf
Department of Anthropology, Texas A&M University, College Station, TX, USA

Definition

Arctic geoarchaeology is concerned with how natural processes affect archaeological site formation in high-latitude northern environments. Perhaps the most significant site formation issue that produces the most serious problems in Arctic geoarchaeology is cryoturbation, which is the effect of repetitive freezing and thawing on sediment and soil. Frost heaving, gelifluction, and ice wedging are the most common cryoturbation processes that can significantly alter archaeological site matrices, disturbing stratigraphic order and displacing artifacts vertically and horizontally.

Frost heaving

Frost heaving results from upward movement of ground materials during freeze-thaw events (Taber, 1929). At archaeological sites, this process can reorient artifacts and ecofacts (Johnson and Hansen, 1974; Johnson et al., 1977). Much of the Arctic is underlain by permafrost, which is soil or other substrate that is permanently frozen, often to great depths. In the warm months, the upper, active layer of the ground thaws, but the still frozen base prevents drainage, leaving the surface generally covered by wet, hydromorphic soils. Winter brings freezing conditions and ice forms within the saturated, frost-susceptible sediment. As it does, it expands upward in the direction of heat loss (Konrad, 1999), which is the only direction in which it can expand as it is blocked by permafrost below. This upward movement squeezes large objects such as rocks and artifacts as freezing water expands in volume with great force, thrusting them upward as well (Bowers et al., 1983). Under certain conditions, frost heaving eventually produces patterned ground, where the repeated freeze-thaw cycles sort large stones and finer sediments into polygonal or linear geometrical shapes (Kessler and Werner, 2003). The longer an artifact is in the ground, the more it can be displaced (Johnson et al., 1977).

Telltale signs at sites affected by frost heaving include (1) large-sized artifacts found in on-surface or near-surface positions and (2) vertical orientation of buried, displaced artifacts (Schweger, 1985). Archaeological sites in areas of tundra, especially sites of greater age, can be completely unstratified through the effects of frost heaving acting over many centuries to move artifacts from initially layered deposits below ground to mostly near-surface positions (Thorson, 1990; Holliday, 2004, 279).

Gelifluction

The process of gelifluction occurs where snowfall accumulation is great, sediment overlying permafrost annually thaws and refreezes, and the ground surface is sloped. Rapid melting of snowfall in spring saturates the upper sediment zone. On a slope, saturated sediment succumbs to gravity, flowing or creeping downslope over the underlying impermeable permafrost zone. Displaced materials then refreeze in their new locations during autumn, creating ribbon-like involutions or folds of the upper sediment zone and displacing associated archaeological materials both vertically and laterally. As the lobes of gelifluctted sediment bulge downhill, they can attenuate upslope cultural deposits, thinning them sometimes to the point of leaving gaps as the mobile material bunches and folds over itself downslope (Hopkins and Giddings, 1953; Thorson and Hamilton, 1977; Holliday, 2004, 279–281).

Ice wedging

Ice wedges form when sediment overlying permafrost becomes freeze-dried, contracts, and cracks under the cold, winter conditions. Due to tensional forces acting on the sediment, these cracks form in a polygonal pattern on the ground surface (patterned ground), but below the surface, the cracks can penetrate to permafrost depth. During the summer months, snowmelt seeps into and fills the cracks and then refreezes during the subsequent winter months. As this water freezes, it expands to form an ice wedge. The following year, the cycle repeats as the ice wedge cracks and seepage fills it again. The process continues so that year after year this cycle of crack, thaw, and freeze widens and deepens the ice wedge. The implications for geoarchaeology are that surface sediment and artifacts can slip down into the cracks, entrained by meltwater seepage, as additional materials filling the ice wedges as they grow. As ice thaws, deformed fill features or ice-wedge pseudomorphs are left behind (Lachenbruch, 1962).

Pseudo-paleosols

A further behavior of soils in Arctic environments involves the concentration of fine particulate matter to form dark layers resembling buried paleosols. Under moist but not saturated soil conditions, thin layers of organic material, clays, and silts can be sorted by the freezing process seasonally, creating a layer that, in warmer months, traps downward moving illuvium, thereby producing color banding that appears to be a buried ancient soil (Thorson, 1990, 406; Holliday, 2004, 281).

Cryoturbation in pleistocene age sites

During the glacial advances of the Pleistocene epoch, Arctic-like conditions moved southward in step with the expanding ice sheets and down the slopes of high mountains carried by the ice flows emanating from upper elevations. Ancient sites dating to the last ice age can also display signs of cryoturbation given the extreme cold of the time. Lower and Middle Paleolithic remains in Britain are often found in alluvial terrace fill, which preserves the best record of such periods (Basell et al., 2011). Cryoturbation features illustrating the effects of frost heaving, gelifluction, and ice wedges have been found in such sites indicating periglacial or frost conditions (Basell et al., 2011, 29). Similarly, the effects of cold conditions due to the Last Glacial Maximum can be seen in the sediments and soils of Upper Paleolithic sites buried in alluvium in the Kostenki area along the Don River in southwest Russia (Holliday et al., 2007). On the Seward Peninsula of western Alaska, a fluted-point site dating to 12,400 calendar years ago shows evidence of cryoturbation in the form of frost-shattered grains and lenticular pores, suggesting the presence of ice in the soil (Goebel et al., 2013).

Bibliography

Basell, L. S., Brown, A. G., Hosfield, R. T., and Toms, P. S., 2011. The geoarchaeology of Paleolithic rivers of southwest Britain. In Brown, A. G., Basell, L. S., and Butzer, K. W. (eds.), *Geoarchaeology, Climate Change, and Sustainability*. Boulder, CO: Geological Society of America, pp. 23–36. GSA special paper, 476.

Bowers, P. M., Bonnichsen, R., and Hoch, D. M., 1983. Flake dispersal experiments: noncultural transformation of the archaeological record. *American Antiquity*, **48**(3), 553–572.

Goebel, T., Smith, H. L., DiPietro, L., Waters, M. R., Hockett, B., Graf, K. E., Gal, R., Slobodin, S. B., Speakman, R. J., Driese, S. G., and Rhode, D., 2013. Serpentine Hot Springs, Alaska: results of excavations and implications for the age and significance of northern fluted points. *Journal of Archaeological Science*, **40**(12), 4222–4233.

Holliday, V. T., 2004. *Soils in Archaeological Research*. Oxford: Oxford University Press.

Holliday, V. T., Hoffecker, J. F., Goldberg, P., Macphail, R. I., Forman, S. L., Anikovich, M., and Sinitsyn, A., 2007. Geoarchaeology of the Kostenki-Borshchevo sites, Don River, Russia. *Geoarchaeology*, **22**(2), 181–228.

Hopkins, D. M., and Giddings, J. L., Jr., 1953. Geological background of the Iyatayet archaeological site, Cape Denbigh, Alaska. *Smithsonian Miscellaneous Collections*, **121**(11), 1–33.

Johnson, D. L., and Hansen, K. L., 1974. The effects of frost-heaving on objects in soils. *Plains Anthropologist*, **19**(64), 81–98.

Johnson, D. L., Muhs, D. R., and Barnhardt, M. L., 1977. The effects of frost-heaving on objects in soils, II: Laboratory experiments. *Plains Anthropologist*, **22**(76), 133–147.

Kessler, M. A., and Werner, B. T., 2003. Self-organization of sorted patterned ground. *Science*, **299**(5605), 380–383.

Konrad, J.-M., 1999. Frost susceptibility related to soil index properties. *Canadian Geotechnical Journal*, **36**(3), 403–417.

Lachenbruch, A. H., 1962. *Mechanics of Thermal Contraction Cracks and Ice-Wedge Polygons in Permafrost*. New York: Geological Society of America.

Schweger, C., 1985. Geoarchaeology of northern regions: lessons from cryoturbation at Onion Portage, Alaska. In Stein, J. K., and Farrand, W. R. (eds.), *Archaeological Sediments in Context*. Orono, Maine: Center for the Study of Early Man, Institute for Quaternary Studies, University of Maine, Orono, pp. 127–141.

Taber, S., 1929. Frost heaving. *The Journal of Geology*, **37**(5), 428–461.

Thorson, R. M., 1990. Geologic contexts of archaeological sites in Beringia. In Lasca, N. P., and Donahue, J. (eds.), *Archaeological Geology of North America. Centennial Volume*. Boulder, CO: Geological Society of America, Vol. 4, pp. 399–420.

Thorson, R. M., and Hamilton, T. D., 1977. Geology of the Dry Creek site: a stratified early man site in interior Alaska. *Quaternary Research*, **7**(2), 149–176.

Cross-references

Beringia, Geoarchaeology
Glacial Settings
Kostenki, Russia

ARTIFACT CONSERVATION

Dennis Piechota
Department of Anthropology, Fiske Center for Archaeological Research, University of Massachusetts at Boston, Boston, MA, USA

Definition

Conservation of archaeological finds is a critical part of excavation and curation. It is the activity that assures the permanence of the physical artifacts and preservation of the information they contain, and it includes specific methods and standards for examination, documentation, treatment, and preventive care of archaeological materials. These activities are performed by specialists who belong to professional societies that promote education, research, and adherence among its practitioners to a code of ethics and standards of practice.

History

When an early human repaired or rejuvenated a stone tool to extend its working life, he was not engaged in conservation as we now understand the term since the preserving activity did not result from an academic tradition of research and education to explore and improve upon the suitability and compatibility of methods and materials. In Europe, it was not until the Renaissance when such an approach was applied to antiquities; sixteenth-century restoration practices were recorded by Benvenuto Cellini in his memoirs (Cellini, 1823). Subsequent discoveries of fragile finds at archaeological sites in Egypt, Italy, the Near East, and elsewhere showed the need for a disciplined approach to the development of preservation practices based on testable methods. In the eighteenth and nineteenth centuries, that need was met by the application of the scientific method in what would eventually become the field of materials science. Investigations of specific ancient materials began the process of consolidating the research and recommended methods of the previous century; these appeared in texts such as *The Preservation of Antiquities* by Friedrich Rathgen (1905) and a book of the same title by Harold Plenderleith (1934) which was subsequently expanded and updated as *The Conservation of Antiquities and Works of Art: Treatment, Repair and Restoration* until its final printing (1974). The discovery of Tutankhamen's tomb with its wealth and diversity of antiquities spurred research in archaeological materials science at the British Museum under Arthur Lucas (1926). These efforts together with those of other research centers formed the foundations of what would become academic postgraduate or certificate programs of study starting in the 1930s at Harvard's Fogg Art Museum and University College London's Institute for Archaeology. Today, universities and other cultural organizations throughout the world train conservators in graduate schools and certificate programs. Worldwide professional societies, such as the International Institute for Conservation (IIC) and the American Institute for Conservation of Historic and Artistic Works (AIC), support conservators by sponsoring journals and congress proceedings for the publication of juried research. UNESCO's International Council of Museums supports the Council for Conservation (ICOM-CC), which hosts a worldwide triennial congress of conservation.

Professional activities

This entry will introduce the professional activities of the conservator. Recent comprehensive studies can be found in *Conservation Treatment Methodology* (Appelbaum, 2007); *Conservation Skills: Judgement, Method, and Decision Making* (Caple, 2000); *Contemporary Theory of Conservation* (Muñoz Viñas, 2005); and *Conservation: Principles, Dilemmas and Uncomfortable Truths* (Richmond and Bracker, 2009).

Examination

Conservators examine artifacts to determine composition and condition prior to considering whether a treatment is needed. They approach every artifact individually and spend a considerable amount of time in this initial phase. Typical protocols for examination start with naked eye inspection under standard and raking visible light as well as ultraviolet light to detect common autofluorescent materials. Microscopic analysis often follows using a - low-power reflected light inspection microscope to begin characterizing minor components. Micro-sampling of these components may be done at this point and the samples mounted for polarizing transmitted light microscopy to further identify and describe the actual physical condition of the artifact. More technical examinations include x-ray fluorescence spectroscopy and x-ray diffraction to identify elemental and mineral components, respectively. Many other analytical methods are used as needed.

Though examinations are done in preparation for treatment, thorough explorations of artifacts whose construction is unfamiliar to specialists in the field can become ends in themselves, and they may be published without reference to any treatment phase under the rubric of technical studies. For example, in their paper "An Egyptian cartonnage of the Graeco-Roman period: Examination and discoveries," Scott et al. (2003) relate their discovery of unexpected pigments and construction techniques in a 350 BC coffin liner from ancient Egypt. Here, the conservators and conservation scientists brought together diverse technologies such as radiocarbon dating, x-ray diffraction analysis, energy-dispersive x-ray fluorescence, Fourier transform infrared spectroscopy (FTIR), thin-layer chromatography, and gas chromatography with mass spectrometry (GC-MS) to show the influence of contact with Roman culture on traditional Egyptian practices.

Documentation

The results of each artifact examination are recorded in a standardized treatment database along with other essential information, such as dimensions, detailed condition descriptions, and photo-documentation. The practice of photographing artifacts before and after treatment is a hallmark of conservation, as the appearance of artifacts can change due to the treatment. Care is taken to record accurately those characteristics of identification and condition such as color, surface condition, completeness, and size. Catalog numbers are always included in the frame of the photograph along with a color balance card and metric measurement scale. Typically, at least six overviews are taken of three-dimensional objects, four side views, a top view, and a bottom view. Additional close-ups or detail views are added as needed to document the pretreatment state. The importance of documentation and especially photo-documentation has caused these practices to be periodically codified through publication. See, for example, *The AIC Guide to Digital Photography and Conservation Documentation* (Warda, 2011).

Treatment

Proposed treatments are determined by the preceding examination. Because the artifacts are considered to contain archaeological data, the conservator generally limits treatment as much as possible to stabilization, and materials applied in this process should be removable, i.e., procedures should be reversible in the ideal. Waterlogged wood objects will crack when dried in air, so they receive treatments with intracellular bulking agents, such as polyethylene glycol, to maintain their dimensions after drying. Without such treatment, the wood might deform into a shape having no resemblance to either its original form or that which it had when recovered in the field. After recovery, some metal artifacts can begin to corrode rapidly in air; these will require treatments to remove the soluble salts that catalyze such corrosion. Textiles and other fibrous artifact fragments are among the most challenging to conserve. They can disintegrate during initial field inspection and, as a result, often require a method called blocklifting, wherein the artifact is kept encased in its surrounding soil or sediment and the entire sediment block is removed to a conservation laboratory where it can be micro-excavated under controlled conditions. Heavily corroded artifacts and complex composite artifacts can also require block retrieval. The care and ingenuity that such lifting techniques require in the field are described in Robert Payton's edited volume, *Retrieval of Objects from Archaeological Sites* (1992), including the recovery of 30 ton sculptures from Argo Island on the Nile and the extremely fragile human remains at Herculaneum.

Often excavations can be collaborative with the archaeologist and conservator listening closely to the wishes of the local community, including heritage groups and descendant groups. *Collaborating at the Trowel's Edge*, an edited volume by Steven Silliman (2008), and *Preserving What Is Valued*, by Miriam Clavir (2002), describe the breadth and complexity of the working relationships that result from community-based research. Such relationships can change the routine academic priorities of conservation performed simply as data preservation. Indigenous peoples are often collaborators with a strong concern for how the earth and its recovered artifacts are handled during and after an excavation. Sacred artifacts will usually receive no conservation treatment in order to preserve their unique unaltered state and avoid leaving preservative agents within the artifact that may be viewed as contaminants. Nonsacred artifacts having special significance to the local community will often receive extra conservation care as these objects often become symbols of local heritage.

Preventive care

Conservators limit the preservative chemicals they apply to all cultural objects. Archaeological collections that are curated primarily for their data require even greater attention because any resinous coating, consolidant, or other chemical can interfere with future chemical analyses. The archaeological conservator then attempts to provide preservation to control physical and environmental deterioration. These can include custom cushioned storage mounts that support weak areas and allow casual inspections without direct handling of the artifact. Termed housing or rehousing techniques, these supports can be enclosed to make passive microenvironmental control possible. Buffered or desiccating silica gel may be added to enclosed storage units or even to individual object housings to limit the range and rate of fluctuation in relative humidity. Instructions for preventive care are often included as part of the treatment database. See Carolyn Rose and Amparo Torres, *Storage of Natural History Collections*, for this aspect of preservation through environmental modification in the museum setting (Rose and de Torres, 1992). In the fieldwork setting, a recent offshoot of this focus on the modification of the environment is the movement toward *P*reservation of *A*rchaeological *R*emains In Situ (PARIS). In this application of preventive care, sites that cannot be excavated for some reason are remotely monitored to prevent damage from, for example, soil water table fluctuations, which could decrease the preservation of organics and metals in burials (Kars and van Heeringen, 2008).

Research

Besides their close work with archaeologists and curators, archaeological conservators also maintain a tradition of research and publication that is independent of the scholarship devoted to the interpretation of artifacts. It is in large measure practical research meant to develop new or improved methods for the examination, analysis, treatment, and care of artifacts. Most investigations of this kind focus on how to characterize the materials of which artifacts are made, how those materials degrade, and how to apply new materials and technologies to their preservation. The research is published mainly in journals of the conservation community's professional societies and institutions, including *Studies in Conservation* (the journal of the International Institute for Conservation), the *Journal of the American Institute for Conservation*, *The Conservator*, the *Journal of the Institute of Conservation* (London), and the Research and Conservation series of the Getty Conservation Institute.

Because conservation is highly interdisciplinary, it also gathers information from wide-ranging areas of research, including anything from the latest filling materials used in modern dentistry to the lives of subterranean termites and the damage they do to wood. Such data are best accessed through two custom online, searchable databases: the Conservation Information Network and Art and the Archaeology Technical Abstracts Online.

Other databases include those that evaluate the common properties of the chemicals and commercial materials used in the treatment of artifacts. They represent an essential resource to conservators because the formulas for commercial materials are changed by their manufacturers over time. Two of these databases are the Conservation and Art Materials Encyclopedia Online (CAMEO) and the Art Materials Information and Education Network (AMIEN). They are always consulted since every treatment requires its own research.

Education

Until the mid-twentieth century, conservation training took the form of apprenticeships under recognized conservators. Archaeological object conservation was a subdivision of museum objects conservation, which tended to concentrate on the aesthetic aspects of artifacts rather than on details such as use-related wear and accretions due to long intervals of surficial deposition or chemical alteration. As archaeological conservation developed, such details became a focus for study and preservation, as they contain information about the unique histories of individual artifacts. This approach is now central to the conservation of artifacts as archaeological data. For example, surface stains that would previously have been removed as disfigurements are now preserved for interpretation by the archaeologist. Ultimately, this trend toward viewing all aspects of an artifact as potential data has led to the current goal of preserving archaeological artifacts in ways that will make the least alteration and leave the fewest residues.

Since the mid-twentieth century, university-based graduate programs in art and historical artifact conservation have emerged around the world, and this is now the dominant way that new practitioners enter the field (though some internship programs continue to offer certificates in select specialties). Since the 1970s, graduate programs have recognized the trend toward specialization and started incorporating museum and field archaeological materials as areas of instruction and study; such programs exist at the University of California at Los Angeles, University College London, and the University of Applied Science in Berlin.

Ethics

Archaeological conservators are charged with recognizing, preserving, and enhancing the information potential of an artifact in ways that do not compromise future study, and they accomplish this without interpreting its meaning, characterizing its place of provenance, function, authorship, or date. This is analogous to preserving a book without commenting on its text. In this role, conservators approach their work very conservatively with respect to actions that change the artifact, even in small ways. For instance, routine artifact cleaning methods must be considered carefully since the wrong application could unintentionally strip off use-related substances or leave behind detergent residues that could confound future organic microanalyses. This position of advocacy for the uninterpreted artifact distinguishes the archaeological conservator from those disciplines that use the collections to reconstruct human behavior. Conservators can sometimes be so protective of cultural property that they seem to discourage any use of it for data acquisition, but, in fact, compromises are always reached that promote stable collections management while facilitating academic study and exhibition. Noninvasive analytical methods are usually promoted over those that require sampling of the artifact. Appropriate handling methods are routinely followed to lessen the wear and tear on artifacts during study. Recently, the issue of preservation sustainability has received increased attention as part of the mix of compromises that the ethical conservator must consider.

Geoarchaeological conservation

The act of unearthing an artifact can create physical and chemical instabilities that often lead to the artifact's deterioration with consequent loss of data. Prior to its excavation, the artifact lies in soil or other sediment, its weight supported by the matrix, and often at chemical and biological equilibrium with its surroundings. When it is first buried, the artifact becomes part of an evolving microenvironment that is related, but not identical, to the general sediment environments of the site. In practical terms, the artifact will either (1) decay, disintegrate, and disappear as an intact object within the site soil, or (2) it will develop a boundary layer at its surface brought about by local geochemical and biological conditions. Examples of these alteration boundaries include simple discolorations, corrosion layers on metal objects, or insoluble salt accretions on wood, ceramics, and other materials. The initial boundary, which can appear as a crust, a softened layer, or a discoloration, can be unstable and invasive, eventually destroying the artifact, or it can be stable and insulating, protecting the artifact from the surrounding sediment. Many materials form such boundary layers. Wooden artifacts, when degrading within wet sediments, will experience a buildup of toxic byproducts at their surfaces that gradually slow the rate of biodeterioration as the artifact – i.e., the food source – becomes less attractive to destructive bacteria and other organisms. Some metal artifacts form thin corrosion layers that transform the object's surface and prevent the underlying metal from further loss. Once formed, such layers must often be preserved along with the rest of the artifact because they may retain the original surface patterning; removing them in order to return the artifact to an unaltered appearance can actually strip away important surface detail. These boundary/alteration layers also yield clues to the geochemistry of the site soil or sediment, providing information that can be used to understand site formation processes. By focusing on preserving the artifact's surficial boundary layer, geoarchaeological evidence relevant to soil conditions, alteration, diagenesis, and other aspects of the burial environment may be conserved.

Summary

Artifact conservation is a young and rapidly developing field. Conservators continue the traditional activity of creating new and better methods of artifact treatment in order to safeguard the collections that form the basis of archaeological inference. At the same time, the conservation profession is evolving and expanding as an academic discipline, offering its own insights into artifact microanalysis and site development processes.

Bibliography

Appelbaum, B., 2007. *Conservation Treatment Methodology.* Oxford: Elsevier.

Caple, C., 2000. *Conservation Skills: Judgement, Method, and Decision Making*. London/New York: Routledge.

Cellini, B., 1823. *Memoirs of Benvenuto Cellini, A Florentine Artist*, trans. by Roscoe, T. London: Wiley & Putnam, 2 vols.

Clavir, M., 2002. *Preserving What is Valued: Museums, Conservation, and First Nations*. Vancouver: UBC Press.

Kars, H., and van Heeringen, R. M. (eds.), 2008. *Preserving Archaeological Remains in situ. Proceedings of the 3rd Conference 7–9 December 2006, Amsterdam*. Geoarchaeological

and Bioarchaeological Studies 10. Amsterdam: Institute for Geo- and Bioarchaeology, Vrije Universiteit.
Lucas, A., 1926. *Ancient Egyptian Materials*. New York: Longmans, Green & Co.
Muñoz Viñas, S., 2005. *Contemporary Theory of Conservation*. Oxford/Boston: Elsevier.
Payton, R. (ed.), 1992. *Retrieval of Objects from Archaeological Sites*. Denbigh/Clwyd/Wales: Archetype.
Plenderleith, H. J., 1934. *The Preservation of Antiquities*. London: The Museums Association.
Plenderleith, H. J., and Werner, A. E. A., 1974. *The Conservation of Antiquities and Works of Art: Treatment, Repair and Restoration*, 2nd edn. London: Oxford University Press.
Rathgen, F., 1905. *The Preservation of Antiquities: A Handbook for Curators*. Cambridge: Cambridge University Press. trans. by Auden, G. A. and H. A.
Richmond, A., and Bracker, A. L. (eds.), 2009. *Conservation: Principles, Dilemmas and Uncomfortable Truths*. Amsterdam/Boston: Elsevier/Butterworth-Heinemann.
Rose, C. L., and de Torres, A. R. (eds.), 1992. *Storage of Natural History Collections: Ideas and Practical Solutions*. Iowa City: Society for the Preservation of Natural History Collections (reprinted 2002).
Scott, D. A., Dennis, M., Khandekar, N., Keeney, J., Carson, D., and Dodd, L. S., 2003. An Egyptian cartonnage of the Graeco-Roman period: examination and discoveries. *Studies in Conservation*, **48**(1), 41–56.
Silliman, S. W. (ed.), 2008. *Collaborating at the Trowel's Edge: Teaching and Learning in Indigenous Archaeology*. Tucson: University of Arizona Press.
Warda, J. (ed.), 2011. *The AIC Guide to Digital Photography and Conservation Documentation*, 2nd edn. Washington, DC: American Institute for Conservation of Historic and Artistic Works.

Cross-references

Ceramics
Chemical Alteration
Electron Probe Microanalyzer
Fourier Transform Infrared Spectroscopy (FTIR)
Gas Chromatography
Glass
Inductively Coupled Plasma-Mass Spectrometry (ICP-MS)
Lithics
Metals
Organic Residues
Radiocarbon Dating
Site Preservation
X-ray Diffraction (XRD)
X-ray Fluorescence (XRF) Spectrometry in Geoarchaeology

ATAPUERCA

Carolina Mallol
Departamento de Geografía e Historia, Universidad de La Laguna, La Laguna, Tenerife, Spain

Definition

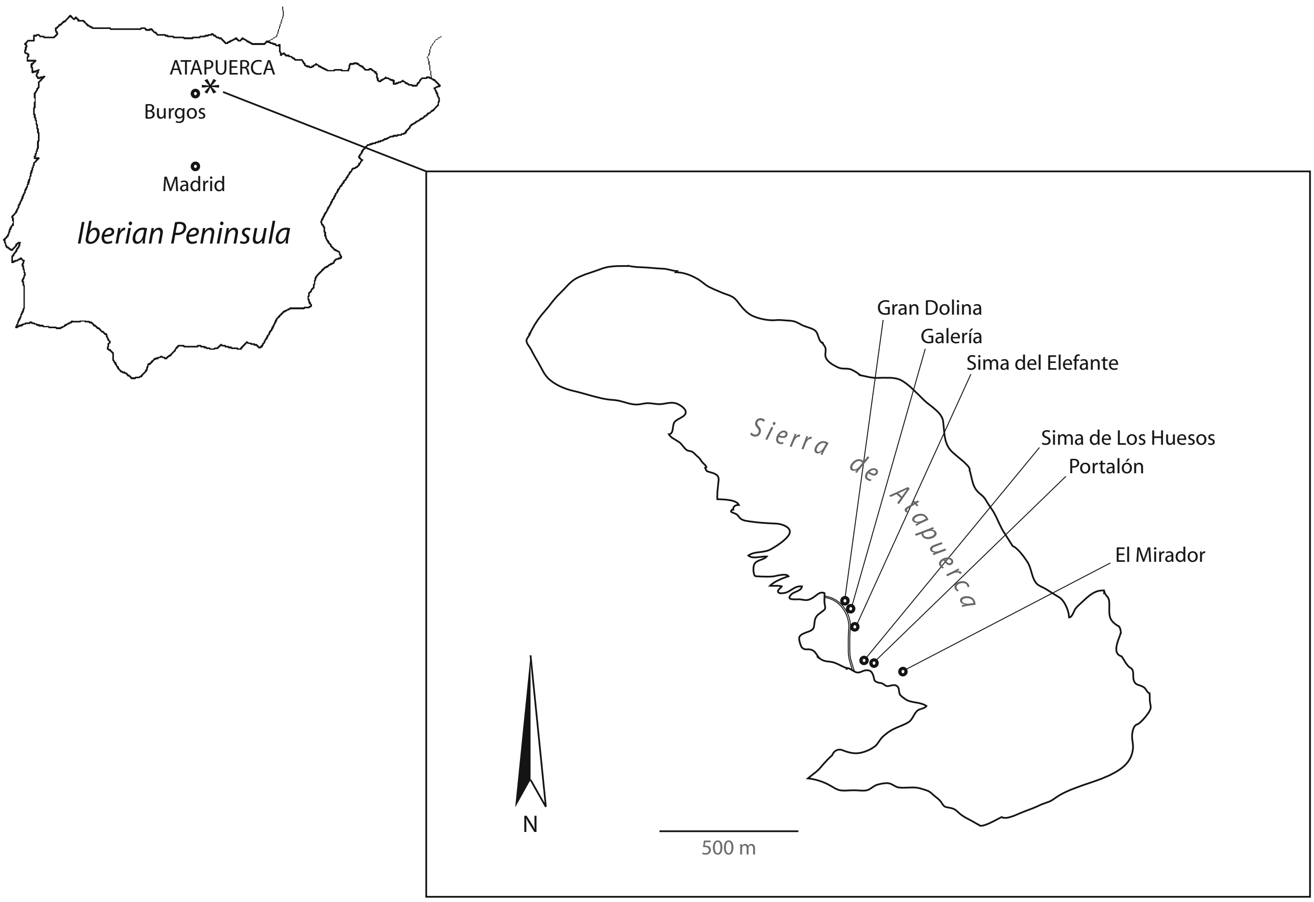
Atapuerca, or Sierra de Atapuerca, is a rich archaeological and paleontological site complex located 12 km east of the city of Burgos, in north central Spain (Figure 1). The sites consist of deeply stratified Lower Pleistocene to Holocene archaeo-sedimentary infills of different karstic caves and conduits within a Mesozoic limestone anticline at the boundary between the Tertiary basins of the Duero and Ebro rivers. Among the key sites, Gran Dolina, Galería, and Sima del Elefante (the railway trench sites) have yielded remains of Lower and early Middle Paleolithic occupations by different hominin species (Carbonell et al., 1999; Rosas et al., 2001; Carbonell et al., 2008). Sima de Los Huesos, a small, paleontologically rich gallery at the end of a 14-m deep sinkhole, has yielded a rich accumulation of hominin skeletal remains (Arsuaga et al., 1991, 1993, 1997, 1999). While the bulk of the Atapuerca sites span the Lower and Middle Pleistocene, two sites, El Mirador and Portalón, include Holocene deposits: Neolithic and Bronze Age remains have been explored in El Mirador (Vergès et al., 2002; Cáceres et al., 2007; Cabanes et al., 2009), and occupations from Upper Paleolithic to the Middle Ages have been found in Portalón (Carretero et al., 2008; Ortega et al., 2008).

All of the deposits are characteristic of cave entrance settings and consist of mixed quartz sand and sandy aggregates from nearby soils, red clay originating within the local karstic system, and limestone rubble from the immediate surroundings. The stratified sequences from the different sites each record a succession of high and low energy modes of gravitational deposition, including debris flows, runoff, and roof spall facies, as well as exokarstic stratified and microstratified waterlain deposits (Vallverdú 1999, 2001; Pérez-González et al., 2001; Mallol and Carbonell, 2008). None of the depositional sequences are continuous, and stratigraphic unconformities are frequent. The Holocene deposits from Portalón and El Mirador are primarily anthropogenic.

Postdepositional carbonate and phosphate diagenesis is prominent throughout the Pleistocene deposits. Overall preservation of bone is good, the smaller-than-2 cm fraction being most affected by diagenetic breakdown linked to decalcification. The Atapuerca flint comprises two geological types – one Neogene and the other Cretaceous in age. The former is highly susceptible to diagenesis due to its elevated percentage of moganite (a polymorph of quartz), and recovered artifacts made with this flint type are often found in poor states of preservation.

The Gran Dolina-TD6 deposit shows pedogenic evidence of calcareous brown soils suggestive of an Atlantic climate and sharp facies changes indicative of strong climatic fluctuations (Vallverdú et al., 2001). In contrast, the rest of the Gran Dolina and Galería deposits are weakly decalcified and bioturbated indicating a mixed Mediterranean/continental temperate climate (Pérez-González et al., 2001).

In-situ human occupation floors have been documented at Galería in layers GII and GIII, as well as in Gran Dolina layers TD10 and TD6, the latter in association with cut-marked human remains. No evidence of anthropogenic fire has been identified in any of the Pleistocene deposits. The Holocene sites, Mirador and Portalón, have yielded well-preserved combustion features and ashy



Atapuerca, Figure 1 Location of Sierra de Atapuerca and the main archaeological sites mentioned in the text. The curved line adjacent to the sites represents a railway trench that exposed the archaeological deposits.

anthropogenic deposits. Rich stabling deposits and human burials dating to the Bronze Age have also been documented at Mirador (Cáceres et al., 2007; Angelucci et al., 2009; Carrancho et al., 2009).

Bibliography

Angelucci, D. E., Boschian, G., Fontanals, M., Pedrotti, A., and Vergès, J. M., 2009. Shepherds and karst: the use of caves and rock-shelters in the Mediterranean region during the Neolithic. *World Archaeology*, **41**(2), 191–214.

Arsuaga, J. L., Carretero, J. M., Martínez, I., and Gracia, A., 1991. Cranial remains and long bones from Atapuerca/Ibeas (Spain). *Journal of Human Evolution*, **20**(3), 191–230.

Arsuaga, J. L., Martínez, I., Gracia, A., Carretero, J. M., and Carbonell, E., 1993. Three new human skulls from the Sima de los Huesos Middle Pleistocene site in Sierra de Atapuerca. Spain. *Nature*, **362**(6420), 534–537.

Arsuaga, J. L., Bermúdez de Castro, J. M., and Carbonell E. (eds.), 1997. Special issue: Sima de los Huesos. *Journal of Human Evolution*, **33**(2–3), 105–421.

Arsuaga, J. L., Lorenzo, C., Carretero, J. M., Gracia, A., Martínez, I., García, N., Bermúdez de Castro, J. M., and Carbonell, E., 1999. A complete human pelvis from the Middle Pleistocene of Spain. *Nature*, **399**(6733), 255–258.

Cabanes, D., Burjachs, F., Expósito, I., Rodríguez, A., Allué, E., Euba, I., and Vergès, J. M., 2009. Formation processes through archaeobotanical remains: the case of the Bronze Age levels in El Mirador Cave, Sierra de Atapuerca, Spain. *Quaternary International*, **193**(1–2), 160–173.

Cáceres, I., Lozano, M., and Saladié, P., 2007. Evidence for Bronze Age cannibalism in El Mirador Cave (Sierra de Atapuerca, Burgos, Spain). *American Journal of Physical Anthropology*, **133**(3), 899–917.

Carbonell, E., Bermúdez de Castro, J. M., and Arsuaga J. L. (eds.), 1999. Special issue: Gran Dolina Site: TD6 Aurora Stratum (Burgos, Spain). *Journal of Human Evolution*, **37**(3–4), 309–700.

Carbonell, E., Bermúdez de Castro, J. M., Parés, J. M., Pérez-González, A., Cuenca-Bescós, G., Ollé, A., Mosquera, M., Huguet, R., van der Made, J., Rosas, A., Sala, R., Vallverdú, J., García, N., Granger, D. E., Martinón-Torres, M., Rodríguez, X.-P., Stock, G. M., Vergès, J. M., Allué, E., Burjachs, F., Cáceres, I., Canals, A., Benito, A., Díez, C., Lozano, M., Mateos, A., Navazo, M., Rodríguez, J., Rosell, J., and Arsuaga, J. L., 2008. The first hominin of Europe. *Nature*, **452**(7186), 465–469.

Carrancho, Á., et al. 2009. Rock-magnetic analyses as a tool to investigate archaeological fired sediments: a case study of Mirador cave (Sierra de Atapuerca, Spain). *Geophysical Journal International*, **179**(1), 79–96.

Carretero, J. M., Ortega, A. I., Juez, L., Pérez-González, A., Arsuaga, J. L., Pérez-Martínez, R., and Ortega, M. C., 2008. A late Pleistocene-Early Holocene archaeological sequence of Portalón de Cueva Mayor (Sierra de Atapuerca, Burgos, Spain). *Munibe Antropologia-Arkeologia*, **59**, 67–80.

Mallol, C., and Carbonell, E., 2008. The collapse of Gran Dolina Cave, Sierra de Atapuerca, Spain: site formation processes of layer TD10-1. *Geoarchaeology*, **23**(1), 13–41.

Ortega, A. I., Juez, L., Carretero, J. M., Arsuaga, J. L., Pérez-González, A., Ortega, M. C., Pérez, R., Pérez, A., Rodríguez, A. D., Santos, E., García, R., Gómez, A., Rodríguez, L., Martínez de Pinillos, M., and Martínez, I., 2008. The Portalón at Cueva Mayor (Sierra de Atapuerca, Spain): a new archaeological sequence. In Diniz, M. (ed.), *The Early Neolithic in the Iberian Peninsula: Regional and Transregional Components*. Oxford: Archaeopress. Proceedings of the XV World Congress (Lisbon, 4–9 September 2006). British Archaeological Reports, International Series, Vol. 1857, pp. 3–9.

Pérez-González, A., Parés, J. M., Carbonell, E., Aleixandre, T., Ortega, A. I., Benito, A., and Martín Merino, M. A., 2001. Geologie de la Sierra de Atapuerca et stratigraphie des remplissages karstiques de Galeria et Dolina (Burgos, Espagne). *L'Anthropologie*, **105**(1), 27–43.

Rosas, A., Pérez-González, A., Carbonell, E., van der Made, J., Sánchez, A., Laplana, C., Cuenca-Bescós, G., Parés, J. M., and Huguet, R., 2001. Le gisement pléistocène de la "Sima del Elefante" (Sierra de Atapuerca, Espagne). *L'Anthropologie*, **105**(2), 301–312.

Vallverdú, J., 1999. Microfacies y micromorfología de las unidades GII y GIII de Galería (Sierra de Atapuerca). In Carbonell, E., Rosas, A., and Díez, J. C. (eds.), *Atapuerca: Ocupaciones humanas y paleoecología del yacimiento de Galería*. Zamora: Junta de Castilla y León, pp. 43–54.

Vallverdú, J., Courty, M.-A., Carbonell, E., Canals, A., and Burjachs, F., 2001. Les sédiments d'*Homo antecessor* de Gran Dolina. (Sierra de Atapuerca, Burgos, Espagne). Interprétation micromorphologique des processus de formation et enregistrement paléoenvironnemental des sédiments. *L'Anthropologie*, **105**(1), 45–69.

Vergès, J. M., Allué, E., Angelucci, D. E., Cebrià, A., Díez, C., Fontanals, M., Manyanós, A., Montero, S., Moral, S., Vaquero, M., and Zaragoza, J., 2002. La Sierra de Atapuerca durante el Holoceno: Datos preliminares sobre las ocupaciones de la Edad del Bronce en la Cueva de El Mirador (Ibeas de Juarros, Burgos). *Trabajos de Prehistoria*, **59**(1), 107–126.

Cross-references

Cave Settings
Chemical Alteration
Lithics
Paleoenvironmental Reconstruction
Site Formation Processes

B

BERINGIA, GEOARCHAEOLOGY

Joshua D. Reuther[1,2] and Ben A. Potter[2]
[1]University of Alaska Museum of the North, Fairbanks, AK, USA
[2]Department of Anthropology, University of Alaska Fairbanks, Fairbanks, AK, USA

The Bering Land Bridge and Beringia: definitions and geography

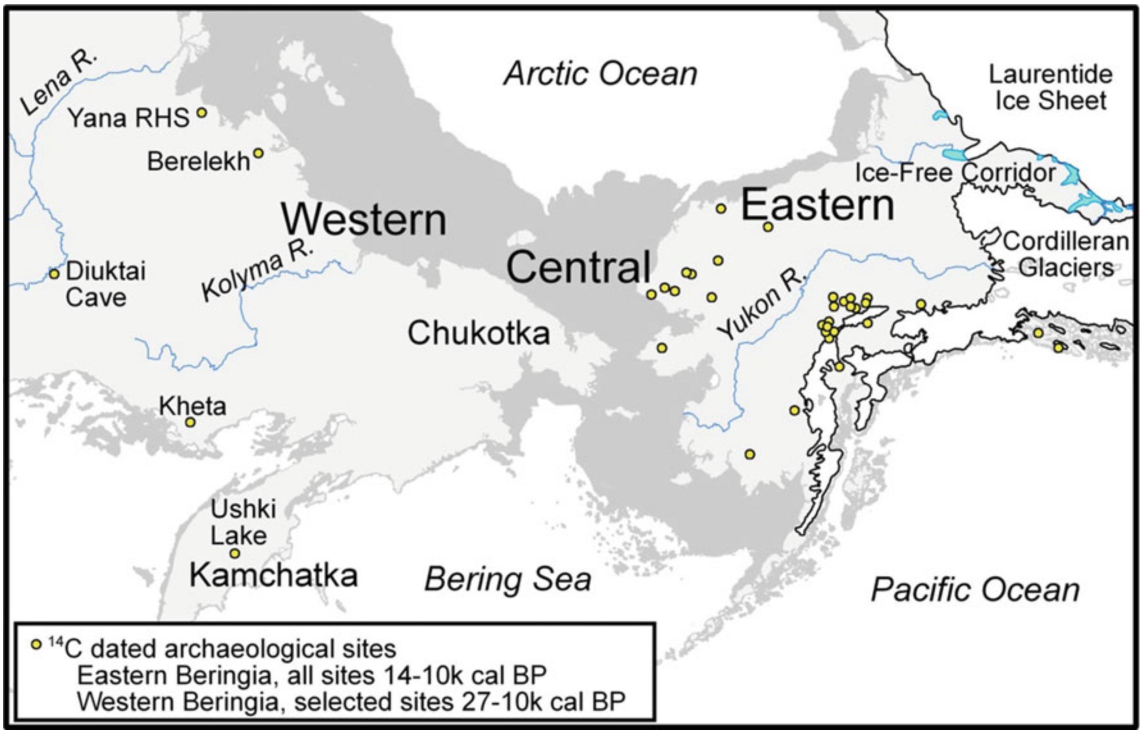
The relatively shallow Bering Sea continental shelf lies between the Arctic and Pacific Oceans separating the coasts of Alaska and Siberia (Figure 1); it was exposed during periods of extensive continental glaciation, as moisture was locked up in the glaciers and sea level dropped about 100 m below modern levels. The exposure of this shelf established what is referred to as the Bering Land Bridge, a nearly 1,000 km wide land-based connection between northeastern Asia and northwestern North America. This area, when exposed, forms the once ∼34 million acre continental mass known as Beringia (Hopkins, 1959; Hultén, 1968; Barber, 2005). During the major episodes of glaciation of the Pleistocene, the extensive northern North American Laurentide and Cordilleran ice sheets coalesced in the region of Alberta, Canada, creating barriers for biotic migration to the east and south. During this period, Alaska and portions of far northwestern Canada were effectively part of northeastern Asia, permitting the exchange of animals, flora, and humans between the two continents and forming the unique blend of Asiatic and North American biotic and cultural systems (Hultén, 1968; Hopkins et al., 1982; Guthrie, 1990; Hoffecker and Elias, 2007).

Hultén (1968) first coined the term "Beringia" to refer to the Bering Land Bridge itself; however, its use has taken on a variety of geographic meanings. Others have broadened the geographic boundaries for the term to include extensive portions of unglaciated Northeast Asia, Alaska, and the Yukon and Northwest Territories of Canada (see Hopkins et al., 1982; Hoffecker and Elias, 2007; and Dixon, 2013 for excellent discussions on the history of the concepts of the Bering Land Bridge and Beringia).

Typically, Beringia has been subdivided into three regions: central, eastern, and western. The unglaciated areas of Northeast Asia, generally from the eastern Siberian Verkhoyansk Range to the western shores of the Bering Strait, comprise western Beringia, while those of Alaska, Yukon, and the Northwest Territories compose eastern Beringia. The area of the Bering Land Bridge itself is usually referred to as central Beringia (West, 1981; Hoffecker and Elias, 2007), consisting of the submerged lowlands of the Bering Sea continental shelf and the former highlands that are now the islands of the Bering and Chukchi Seas. Others have recently extended the definition of Beringia to include portions of southeastern Alaska and the northwestern coast of British Columbia that were once exposed unglaciated lands along coastlines during the Last Glacial Maximum (LGM: 23,000–19,000 cal BP; Dixon, 2013).

The exposure of the Bering Land Bridge forced the oceanic moisture sources of the Pacific and Arctic Oceans farther away from interior regions of Beringia. During the LGM, coastal air masses that currently provide moisture to eastern Siberia, Alaska, and northwestern Canada had to travel farther, and the large glacial masses in the mountain ranges became moisture barriers for the interior regions of Beringia (Manley, 2002; Brigham-Grette et al., 2004). This situation fostered periods of extreme continentality in the climate, exceptionally clear skies, and a remarkable environment that has no distinct modern analog (Guthrie, 1990, 2001; Anderson and Brubaker, 1994). Across the regions of Beringia, glaciated and

A.S. Gilbert (ed.), *Encyclopedia of Geoarchaeology*, DOI 10.1007/978-1-4020-4409-0,



Beringia, Geoarchaeology, Figure 1 Map of Beringia showing exposed continental shelf and North American glacial extent at 14,000 cal BP, during the initial colonization of the Americas (Sea level and glacial ice distributions are derived from Manley (2002) and Dyke et al. (2003), respectively. Eastern Beringian archaeological site data are from Potter et al. (2013)).

periglacial environments provided the dominant geological processes that controlled depositional regimes, geomorphology, and pedogenic development. Beringian high latitude environments were some of the last Asian regions to be colonized by humans (Goebel, 1999; Hoffecker and Elias, 2007; but cf. Pitulko et al., 2004 and below), and the same adaptive strategies (high residential mobility, possibly microblade technology, and large mammal hunting) apparently enabled expansion into the Americas (Goebel et al., 2008).

Beringian paleoenvironments

The Last Glacial Maximum

There has been considerable discussion as to the general characteristics of the Beringian environment during the LGM, which is understandable given Beringia's vastness. In the 1980s and 1990s, two dichotomous views of the general Beringian environment colored most of this discussion: a barren polar desert versus relatively biologically diverse steppe tundra "grassland."

Glaciers and their associated outwash deposited an immense amount of silt and sand deposits into drainages; these deposits were subsequently redeposited across much of the Beringian landscapes through wind mobilization. Higher landforms nearest to glaciers were stripped of overlying unconsolidated sands and silts by high-energy katabatic winds creating ventifacted surfaces (Péwé, 1975, 1977). Landscapes farther away from glaciers developed sand sheets and extensive loess (wind-blown silt) deposits that capped hilltops, terraces, and fans.

Loessic and fluvial deposits across Beringia have yielded prodigious amounts of animal fossils dating to the LGM and earlier periods (Guthrie, 1990; Ukraintseva et al., 1996; Froese et al., 2009; Boeskorov et al., 2014). Steppe bison (*Bison priscus*), Yukon horse (*Equus lambei*), and woolly mammoth (*Mammuthus primigenius*), in that order, are the most prevalent species occurring in these deposits in eastern Beringia. Caribou (*Rangifer tarandus*), camel (*Camelops* sp.), musk ox (*Ovibos moschatus*), saiga antelope (*Saiga tatarica*), sheep (*Ovis* sp.), wapiti (elk; *Cervus canadensis*), and yak (*Bos* sp.) were present in lower numbers. Carnivores included short-faced bear (*Arctodus simus*), saber-toothed cat (*Smilodon* sp.), brown bear (*Ursus arctos*), wolf (*Canis lupus*), coyote (*Canis latrans*), and lion (*Felis* sp.). Megafauna were abundant and represented a larger amount of biomass on the Beringian landscape than any that exists in the northern hemisphere today. Many of these species did not survive in eastern Beringia much past the LGM; however, key subsistence species for early humans in the region did survive into the Late Glacial and early Holocene, including bison and caribou (Guthrie, 2006; Potter, 2011).

Based on small and large mammalian fossil assemblages recovered from loessic deposits in eastern Beringia, Guthrie (1968, 1990) proposed that a relatively homogeneous expanse of cold and arid steppe-like grassland, often referred to as the "mammoth steppe," extended east to west from the Yukon, Canada, to northern Europe. This grassland supported a diverse set of grazing megafauna with horse, bison, and mammoth as the dominant large mammal species. Some palynologists suggested, based on pollen influx analyses from lake cores, that the Beringian landscape was covered by sparse tundra during the LGM and could not have supported sizable populations of large mammals (Cwynar and Ritchie, 1980; Colinvaux and West, 1984).

More recent research on insect fossils and buried vegetation indicates that a geographically limited north-south mesic zone, possibly with more shrub tundra vegetation, was present on the exposed Bering Land Bridge (Höfle et al., 2000; Elias and Crocker, 2008). This more mesic zone may have prohibited some species (woolly rhinoceros, bonnet-horned musk ox, and North American camels) from migrating east or west over the land bridge (Guthrie, 2001; Elias and Crocker, 2008). Guthrie (2001) has referred to this mesic region as a north-south-trending "buckle" within the expansive mammoth steppe grasslands. This mesic buckle served as a refugium for mesic-adapted species and a barrier for several grassland-adapted North American and East Asian large mammal and insect species that never crossed the Bering Land Bridge, but inhabited adjacent arid environments (Guthrie, 2001; Elias and Crocker, 2008). Recent paleoecological studies have placed a wider emphasis on regional variation of tundra and shrub communities throughout Beringia with gradients of xero-, meso-, and hydrophytic plants depending on more local factors such as available moisture, evapotranspiration rates, soil temperatures, elevation, topography, and aspect (Anderson and Brubaker, 1994; Elias et al., 2000; Brigham-Grette et al., 2004; Zazula et al., 2006; Elias and Crocker, 2008). Thus, the current picture we have of the LGM Beringian climate and environment was highly continental, arid, and treeless across much of the Beringia, with shrubs likely occurring in lowland riparian zones of central Beringia.

During the LGM, central Beringia likely had a greater number of lakes than eastern Beringia (Ager, 2003), probably due to an east-west moisture gradient and potential difference in evapotranspiration rates (Guthrie, 2001). Many of the lakes in eastern Beringia were not initiated until after 15,000 cal BP as a consequence of the highly arid environment of the LGM (Shuman and Finney, 2007).

Late Glacial and Holocene

Around 18,000–16,000 cal BP, the climate began to ameliorate, and the extreme glacial conditions began to abate, which marks the beginning of the Late Glacial period. By 16,000 cal BP, shrub tundra vegetation with an increase in the presence of *Betula* (birch) expanded across many parts of eastern Beringia (Bigelow, 2007). *Populus* trees expanded northward beyond their current ranges by 12,900 cal BP (Mann et al., 2002). The expansion of shrub tundra caused widespread zonation of steppe tundra at higher elevations, thereby shrinking and fractionating the distribution of large mammal-grazing habitat (Guthrie, 1990). Humans, moose, and wapiti appear to have migrated into eastern Beringia at roughly the same time, coincident with the expansion of shrubs (Guthrie, 2006; Meiri et al., 2014). However, moose remained a very minor part of the overall subsistence economy throughout the late Pleistocene and Holocene (Yesner, 1989), while wapiti played a more prominent role (Potter, 2005, 2008).

Across Beringia, climatic fluctuation and ecological and landscape changes that were coincident with general hemispheric cooling during the Younger Dryas Chronozone (12,900–11,700 cal BP) seem to have been highly variable across and within regions (Kokorowski et al., 2008; Borzenkova et al., 2013). Several palynological records in western and eastern Beringia document the increase in herbaceous tundra taxa and decrease in woody vegetation (Mann et al., 2002; Kokorowski et al., 2008; Borzenkova et al., 2013), and localized glacial advances coincident with the Younger Dryas have been recorded in mountain ranges in interior, eastern Beringian regions (Briner et al., 2002; Reger et al., 2008). An increase in wind-blown sand deposition is recorded in a limited number of geologic sections in interior eastern Beringia implying localized sparse vegetation, exposed sediment sources, and increased wind intensity (Bigelow et al., 1990; Dilley, 1998). Other paleoenvironmental records, however, show increases in shrub tundra and deciduous species, soil formation, and continuing climatic amelioration (Carlson and Finney, 2004; Hoffecker and Elias, 2007).

Paleofaunal records show a substantial change in the character and distribution of large and small mammal communities that coincide with regional changes in climate, geological environments, and vegetative communities. Habitat reduction, decreases in belowground biomass, introduction of toxic plants, and increases in moisture and paludification have been put forward as some of the primary processes leading to changes in interior Alaskan mammalian biodiversity from the LGM to the Holocene (Guthrie, 1984, 1990, 2001). The distributions of small mammals, such as ground squirrels, large browsers and grazers, and smaller mammals, became more restricted from the Late Glacial into the early Holocene, with some species becoming locally extinct (Guthrie, 1990, 2006; Mann et al., 2013).

The inundation of the Bering shelf and separation of northeastern Asia and western Alaska occurred between 12,000 and 10,000 cal BP (Elias et al., 1996, 1997; Manley, 2002). This inundation reconnected the waters of the Chukchi Sea of the Arctic Ocean to the Bering Sea of the North Pacific Ocean. Air circulation patterns began to fluctuate regionally and seasonally as the heights of the large ice sheets were reduced. Coastal air masses were no longer blocked and bifurcated by the glaciers. The early Holocene maintained a general trend of increased warming and effective moisture. Multiple climate proxies indicate that summer insolation and July temperatures may have reached their maximum between 11,000 and 8,000 cal BP, a period referred to as the Holocene thermal maximum (Kaufman et al., 2004). Deciduous and coniferous forests expanded in many regions of Beringia, as well as paludification (Bigelow, 2007; Borzenkova et al., 2013). Sea-level rise began to stabilize around 6,000 cal BP, reaching modern levels at about 4,700 cal BP (Mason and Jordan, 1993; Mason et al., 1997), and the former highlands of central Beringia became islands and peninsulas.

Beringia: the georchaeological record

Western Beringia

The geoarchaeological record in Western Beringia exhibits considerable variability (see review in Brigham-Grette et al., 2004) and has affected archaeological research strategies. In much of Chukotka and Kamchatka with few exceptions (e.g., Ushki Lake, Kheta), sites have been discovered in areas with relatively little sediment deposition, and surficial (or near surficial) archaeology has largely limited analyses to typological approaches in the absence of deep stratigraphy and secure radiocarbon dating (Dikov, 1997; Slobodin, 1999). A more substantial record of stratified and generally well-dated Late Paleolithic sites (mainly post-LGM) has been discovered along the Lena River and tributaries such as the Aldan River, including Diuktai Cave, Verkhne-Troistakaya, and Ust-Mil 2 (summarized in Mochanov and Fedoseeva, 1996). The Yana RHS (Rhinoceros Horn Site) site (over 70° N. latitude), with an occupation dating to ~28,000 ^{14}C BP, pushes human occupation in Western Beringia to before the LGM (Pitulko et al., 2004; Nikolskiy and Pitulko, 2013).

Much archaeological research has focused on the earliest colonization of Northeast Asia, the presence/absence of humans during the LGM (Goebel, 2002 vs. Kuzmin and Keates, 2005; Kuzmin, 2008; and later papers by Kuzmin), and identifying the ancestors of the earliest Americans (see review in Hoffecker and Elias, 2007).

Many archaeologists have typically used culture history-based approaches to Siberian archaeology, and geology, where it is considered, has been focused on chronology (e.g., Okladnikov, Mochanov, Dikov), though there are examples of more geoarchaeologically informed approaches (e.g., Tseitlin, 1979; Waters et al., 1999; Buvit 2008, 2011). More recently, site-based and regional geoarchaeological approaches have become more common (Nikolskiy et al., 2010; Basilyan et al., 2011; Nikolskiy and Pitulko, 2013). New dating approaches such as OSL dating have been applied with varying success (e.g., Huntley and Richards, 1997; Waters et al., 1999).

The cultural chronology of Western Beringia has seen considerable debate, with various labels applied to the same materials – e.g., the Diuktai, Selemdzha, and Kamchatkan Paleolithic (Mochanov and Fedoseeva, 1996; Dikov, 2004; see Vasil'ev, 1993). The earliest undisputed occupation, at Yana RHS, is a Middle Upper Paleolithic site similar in certain respects to contemporaneous southern Siberian sites (e.g., Mal'ta) and unrelated to the later Diuktai culture, which is associated with widespread post-LGM expansion to into western and eastern Beringia (Yi and Clark, 1985; Goebel, 1999).

Central and eastern Beringia

Archaeological research in central Beringia concentrating on Late Glacial and early Holocene sites has been limited to identifying the potential for submerged landforms dating to these periods through geophysical remote sensing and coring. The only extensive archaeological excavations that have been conducted in central Beringia are on islands that were once the highlands of the Bering Land Bridge; no human occupations have been found that date older than 4,000 cal BP.

Eastern Beringia holds some of the oldest archaeological sites in North America and what has long been suggested as a unique record of technological variability during the Late Glacial and early Holocene that blends Old and New World technological traits (i.e., prismatic core and blade and bifacial projectile point technologies, respectively). The mechanisms that have led to variability in the eastern Beringian record have been highly debated with reasoning invoking stylistic and technological differences among cultural groups, differences in seasonal resource procurement strategies, and variation in raw material quality, abundance, and size and shape.

Many of the sites in the northern part of eastern Beringia (Seward Peninsula, the Brooks Range regions, and northern coastal plain) have been found on bedrock promontories and glacial outwash features. The overlying unconsolidated sediments are generally shallow (<1 m thick) and consist of eolian fine sands and silts and regolith (Reanier, 1982; Rasic, 2011; Goebel et al., 2013). Soils on these landforms above the Arctic Circle tend to cryic in nature and generally either gelisols or inceptisols that form under moist and wet tundra vegetation in cold, dry environments (Ugolini, 1986; Muhs et al., 2000). Podzolization in these regions primarily occurs under the presence of acidic tundra-heath vegetation and at the tree line of the coniferous forests.

The sites that have tended to garner the most attention are those that are associated with what has been termed the "Northern Paleo-Indian tradition" (Dixon, 1993; Reanier, 1995; Smith et al., 2013). Many of these assemblages contain distinctive styles of lanceolate and fluted projectile points that date between 12,900 and 11,200 cal BP and what may be regionally separated into three complexes: the Mesa, Northern Fluted Point, and Sluiceway complexes (Smith et al., 2013). The Mesa site is one of the more well known of these types dating to the Late Glacial and early Holocene and one of the type sites for the Mesa complex. A grouping of sites in the western Brooks Range has formed the basis of the Sluiceway complex (Rasic, 2011). Many sites containing so-called Northern Fluted Points have been used to define the Northern Fluted Point complex, and many of the finds have occurred on the surface of landforms or in very shallow undated contexts (Dixon, 1999). Recently, two sites were excavated in northwestern Alaska, Raven Bluff, and Serpentine Hot Springs that contain buried fluted point assemblages as well as relatively well-defined stratigraphy that has yielded age determinations from 12,400 to 11,200 cal BP (Goebel et al., 2013; Smith et al., 2013).

Microcore and blade technology has been recognized at several of these northern Beringian sites; however, they are generally assumed to have been produced by the later American Paleoarctic tradition or the Denbigh Flint complex (Giddings, 1964; Anderson, 1970) occupations of the region. The shallowness of the overlying unconsolidated sediments along with postdepositional disturbance of the deposits may have created a palimpsest and mixture of different occupations. However, several studies have been able to separate different components and occupations by fine-grained intrasite spatial analyses of activity areas (Bowers, 1982; Bever, 2000; Rasic, 2011). In addition, the lack of sufficient deposition over the archaeological materials makes for poor protection and increases the rate of degradation of organic materials at surface and near-surface sites. Well-preserved faunal remains associated with sites such as these are uncommon, with the exception of caribou at Raven Bluff (Smith et al., 2013).

Other depositional settings in which northern eastern Beringian sites occur are dunes (e.g., Nogahabara I: Odess and Rasic, 2007), caves (e.g., Trail Creek and Bluefish Caves: Larsen, 1968; Cinq-Mars, 1979), and alluvial terraces (e.g., Onion Portage: Anderson, 1988).

The earliest traces of humans in interior eastern Beringia appear to be associated with landscape stability and soil development. Human colonization of interior Alaska occurred during a period of the Late Glacial in which birch (*Betula* sp.) shrubs and likely willow (*Salix* sp.) expanded across the landscape (Bigelow and Powers, 2001; Hoffecker and Elias, 2007). Soil development intensified during the Late Glacial, likely associated with the expansion of shrubs and then dramatically increased throughout the early Holocene as forests began to expand.

In interior Alaska and the Yukon, Canada, relatively deep loess and eolian sand deposits (>1 m thick) contain excellent records of well-stratified soil sequences dating back to the Late Glacial – ~14,500 cal BP (Dilley, 1998; Hoffecker and Elias, 2007; Reuther, 2013), although some landforms in more wind intense environments were partially denuded of unconsolidated fine sediments. Surface and near-surface sites in these environments potentially suffer from similar multiple occupation palimpsest and preservation issues similar to those mentioned above at sites in northern eastern Beringia. In addition, postdepositional movement due to freeze-thaw of sediments (cryoturbation) and downslope movement (solifluction/gelifluction) can become a hindrance to deciphering potentially mixed occupations. Several sites that played a significant role in the development of eastern Beringian archaeology suffered from many of the issues outlined above, including many of those that were used initially to define the Denali Complex (West, 1967, 1975), e.g., the Campus site (Mobley, 1991) and sites around the Tangle Lakes region (West, 1996).

Extensive geological and geoarchaeological investigations have been conducted in two main river valleys in interior eastern Beringia: the Nenana and Tanana. Geoarchaeological studies during the North Alaska Range Early Man Project established a relatively consistent Late Glacial and early Holocene loess and sand sheet depositional sequence with intermittent soil development and landscape stability throughout the Nenana River Valley (Thorson and Hamilton, 1977; Powers and Hoffecker, 1989). Immature tundra soils (Cryothents) were widespread in the Nenana Valley during the Late Glacial and early Holocene occupations, while incipient forest soils (Cryochrepts) began developing later in the Holocene in areas where eolian deposition waned (Thorson and Hamilton, 1977; Power and Hoffecker, 1989). Geological work associated with the project also helped refine the glacial sequences and alluvial terrace development in the region (Ten Brink and Waythomas, 1985). Several important early sites in the Nenana Valley and adjacent valleys are situated on alluvial and outwash terraces and fans, including the Carlo Creek, Dry Creek, Eroadaway, Moose Creek, Owl Ridge, Panguingue Creek, Walker Road, and Teklanika West sites. Several of these sites helped to clarify the antiquity of the Denali Complex (West, 1967, 1975) dating it back to 13,000 cal BP, along with the recognition of an earlier regional and stratigraphically lower occupation, the Nenana Complex, dating back to 13,300 cal BP (Powers and Hoffecker, 1989; Goebel et al., 1991).

Several sites in the Tanana River Valley contain excellent organic preservation due to the rapid accumulation of, and calcareous nature of, the loess (Dilley, 1998; Reuther, 2013) and an incredible wealth of faunal assemblages that date to the Late Glacial and early Holocene. Like the Nenana Valley, immature soils (Cryothents) were widespread in the Tanana Valley during the Late Glacial and early Holocene occupations due to competing processes of soil formation and vegetation growth versus loess deposition. However, the Late Glacial and early Holocene Tanana Valley soils were likely associated with a shrub tundra and scattered open deciduous forest. Incipient forest soil (Cryochrepts) development began in the early part of the Holocene (Dilley, 1998; Potter, 2005; Reuther, 2013), likely associated with an open deciduous forest. As loess deposition decreased throughout the Holocene, coniferous forests and peats began to develop across the Tanana Valley, and landscapes became more stable.

Early sites in the middle and upper portions of the Tanana River Valley reveal a rich history of hunter-gatherer occupations that date back to 14,000 cal BP and the earliest unequivocal evidence for the settlement of northern North America (Holmes, 1996, 2011; Potter et al., 2013). Sites are generally situated on bedrock bluff edges and knolls (e.g., Bachner, Broken Mammoth, Chugwater, Gerstle River, Little John, Mead, McDonald Creek, Swan Point, the Healy Lake Village, and Linda's Point sites) and stabilized sand dunes (e.g., Upward Sun River and Keystone Dune sites) that were adjacent to wetlands during the time of the Late Glacial and early Holocene occupations, which allowed access to a wide diversity of animals, birds, and fish (Yesner, 2007; Potter et al., 2011, 2013). While many of the early sites in eastern Beringia are hunting and secondary processing camps, at least two sites in the middle Tanana Valley are base camps – the Upward Sun River and Mead sites – giving us a glimpse into more residential life, including mortuary practices (Potter et al., 2011, 2013, 2014).

In other regions of interior eastern Beringia, we are just beginning to get a glimpse of the Late Glacial and early Holocene records as more archaeological and geoarchaeological investigations are being conducted. Higher elevation landscapes in the central Alaska Range and the Talkeetna Mountains were used shortly after deglaciation as evident at 11,000–12,000 cal-year-old sites such as Bull River II, Jay Creek Ridge, and the Phipps sites (West et al., 1996; Dixon, 1999; Wygal, 2010).

Late Glacial and early Holocene cave archaeological sites are few in interior eastern Beringia, the most well documented being Lime Hills Cave I in southwestern Alaska with occupations that date back to 12,000 cal BP (Ackerman, 2011). Other caves have yielded important paleontological data dating back to 18,000 cal BP, but they have yet to yield early archaeological remains (Sattler et al., 2001).

The coastal zones of southern Alaska and northwestern British Columbia, beyond what is traditionally viewed as Beringia proper, contained areas that remained unglaciated during the LGM or were deglaciated very early in the Late Glacial period (Carrara et al., 2007; Misarti et al., 2012). These ice-free areas provided habitat for many terrestrial mammals (Heaton and Grady, 2003). Several early sites on raised terraces and in caves in southeastern Alaska and northwestern British Columbia (Dixon et al., 1997; Fedje et al., 2011; Carlson and Baichtal, 2015) date back to 12,000 cal BP. The earliest sites in the islands and peninsulas of the Bering Sea region date to no earlier than 9,500 cal BP (Davis and Knecht, 2010).

Summary

Beringia was a vast and geologically complex region no matter how its borders are defined by researchers. Past terrestrial mammalian diversity through the LGM and into the Late Glacial appears to have been much higher than many of the regions in northern Asia and northern North America today. The marginality of the interior northern environments that we see in these regions today may be more the product of Holocene changes in the climate and environment. During the Late Glacial and early Holocene interval, we see broad similarities in technology, subsistence, and settlement systems across many regions of Beringia. These systems became more regionalized into the Holocene with an adaptation to new changes in landscapes and the abundance and types of resources.

Bibliography

Ackerman, R. E., 2011. Microblade assemblages in southwestern Alaska: an early Holocene adaptation. In Goebel, T., and Buvit, I. (eds.), *From the Yenisei to the Yukon: Interpreting Lithic Assemblage Variability in Late Pleistocene/Early Holocene Beringia*. College Station: Texas A&M University Press, pp. 255–269.

Ager, T. A., 2003. Late Quaternary vegetation and climate history of the central Bering Land Bridge from St. Michael Island, western Alaska. *Quaternary Research*, **60**(1), 19–32.

Anderson, D. D., 1970. Microblade traditions in northwestern Alaska. *Arctic Anthropology*, **7**(2), 2–16.

Anderson, D. D., 1988. *Onion Portage: The Archaeology of a Stratified Site from the Kobuk River, Northwest Alaska*. Fairbanks: University of Alaska Press. Anthropological Papers of the University of Alaska 22(1–2).

Anderson, P. M., and Brubaker, L. B., 1994. Vegetation history of northcentral Alaska: a mapped summary of late-Quaternary pollen data. *Quaternary Science Reviews*, **13**(1), 71–92.

Barber, V., 2005. Land bridges and the Arctic continental shelf. In Nuttal, M. (ed.), *The Encyclopedia of the Arctic*. New York: Routledge, pp. 1150–1151.

Basilyan, A. E., Anisimov, M. A., Nikolskiy, P. A., and Pitulko, V. V., 2011. Wooly mammoth mass accumulation next to the Paleolithic Yana RHS site, Arctic Siberia: its geology, age, and relation to past human activity. *Journal of Archaeological Science*, **38**(9), 2461–2474.

Bever, M. R., 2000. *Paleoindian Lithic Technology and Landscape Use in Late Pleistocene Alaska: A Study of the Mesa Complex*. Ph.D. dissertation, Department of Anthropology, Southern Methodist University, Dallas.

Bigelow, N. H., 2007. Pollen records, late Pleistocene/northern North America. In Elias, S. A. (ed.), *Encyclopedia of Quaternary Science*. Amsterdam: Elsevier, pp. 2633–2648.

Bigelow, N. H., and Powers, W. R., 2001. Climate, vegetation, and archaeology 14,000–9000 cal yr B.P. in central Alaska. *Arctic Anthropology*, **38**(2), 171–195.

Bigelow, N., Begét, J., and Powers, R., 1990. Latest Pleistocene increase in wind intensity recorded in eolian sediments from central Alaska. *Quaternary Research*, **34**(2), 160–168.

Boeskorov, G. G., Potapova, O. R., Mashchenko, E. N., Protopopov, A. V., Kuznetsova, T. V., Agenbroad, L., and Tikhonov, A. N., 2014. Preliminary analyses of the frozen mummies of mammoth (*Mammuthus primigenius*), bison (*Bison priscus*) and horse (*Equus* sp.) from the Yana-Indigirka Lowland, Yakutia, Russia. *Integrative Zoology*, **9**(4), 471–480.

Borzenkova, I.I., Speranskaya, N. A., Bulygina, O. N., Razuvaev, V. N., Karpenko, L. V., Parfenova, E. I., Tchebakova, N. M., Knight, R. W., Korovin, G. N., and Vygodskaya N. N., 2013. Late Glacial and Holocene paleoclimatic reconstructions in Siberia. In Groisman, P. Y., and Gutman, G. (eds.), *Regional environmental changes in Siberia and their global* *consequences*. Springer Environmental Science and Engineering Series. Dordrecht, Netherlands: Springer, pp. 58–60.

Bowers, P. M., 1980. *The Carlo Creek Site: Geology and Archeology of an Early Holocene Site in the Central Alaska Range. Occasional Paper 27*. Fairbanks: Anthropology and Historic Preservation, Cooperative Park Studies Unit, University of Alaska.

Bowers, P. M., 1982. The Lisburne site: analysis and cultural history of a multi-component lithic workshop in the Iteriak Valley, Arctic foothills, northern Alaska. *Anthropological Papers of the University of Alaska*, **20**(1–2), 79–112.

Brigham-Grette, J., Lozhkin, A. V., Anderson, P. M., and Glushkova, O. Y., 2004. Paleoenvironmental conditions in western Beringia before and during the Last Glacial Maximum. In Madsen, D. B. (ed.), *Entering America: Northeast Asia and Beringia Before the Last Glacial Maximum*. Salt Lake City: The University of Utah Press, pp. 29–61.

Briner, J. P., Kaufman, D. S., Werner, A., Caffee, M., Levy, L., Manley, W. F., Kaplan, M. R., and Finkel, R. C., 2002. Glacier readvance during the Late Glacial (Younger Dryas?) in the Ahklun Mountains, southwestern Alaska. *Geology*, **30**(8), 679–682.

Buvit, I., 2008, *Geoarchaeological investigations in the southwestern Transbaikal region, Russia*. Ph.D. dissertation, Washington State University, Pullman.

Buvit, I., Terry, K., Konstantinov, M. V., and Kolosov, V. K., 2011. The alluvial history and sedimentary record of the Priiskovoe site and its place in the Paleolithic prehistory of Siberia. *Geoarchaeology*, **26**(5):616–648.

Carlson, R. J., and Baichtal, J. F., 2015. A predictive model for locating early Holocene archaeological sites based on raised shell-bearing strata in southeast Alaska, USA. *Geoarchaeology*, **30**(2), 120–138.

Carlson, L. J., and Finney, B. P., 2004. A 13 000-year history of vegetation and environmental change at Jan Lake, east-central Alaska. *The Holocene*, **14**(6), 818–827.

Carrara, P. E., Ager, T. A., and Baichtal, J. F., 2007. Possible refugia in the Alexander Archipelago of southeastern Alaska during the late Wisconsin glaciation. *Canadian Journal of Earth Science*, **44**(2), 229–244.

Cinq-Mars, J., 1979. Bluefish Cave I: a late Pleistocene eastern Beringian cave deposit in the northern Yukon. *Canadian Journal of Archaeology*, **3**, 1–32.

Colinvaux, P. A., and West, F. H., 1984. The Beringian ecosystem. *Quarterly Review of Archaeology*, **5**(3), 10–16.

Cwynar, L. C., and Ritchie, J. C., 1980. Arctic steppe-tundra: a Yukon perspective. *Science*, **208**(4450), 1375–1377.

Davis, R. S., and Knecht, R. A., 2010. Continuity and change in the eastern Aleutian archaeological sequence. *Arctic Anthropology*, **82**(5–6), 507–524.

Dikov, N. N., 1997. *Asia at the Juncture with America in Antiquity: The Stone Age of the Chukchi Peninsula*. Translated by Bland, R. L. Anchorage, Alaska: U.S. Department of the Interior, National Park Service, Shared Beringian Heritage Program. Original: Dikov, N. N., 1993, *Aziia na styke s Amerikoi v drevnosti: kamennyi vek Chukotskogo poluostrova* [*Asia at the Crossroads with America in Antiquity*]. Sankt-Peterburg: Nauka.

Dikov, N. N., 2004. *Early Cultures of Northeastern Asia*. Translated by Bland, R. L. Anchorage, Alaska: U.S. Department of the Interior, National Park Service, Shared Beringian Heritage Program. Original: Dikov, N. N., 1979, *Drevnie kul'tury Severo-Vostochnoi Azii: Aziia na styke s Amerikoi v drevnosti* [*Early Cultures of Northeast Asia (Asia at the Crossroads with America in Antiquity)*]. Moskva: Nauka.

Dilley, T. E., 1998. *Late Quaternary Loess Stratigraphy, Soils, and Environments of the Shaw Creek Flats Paleoindian Sites, Tanana Valley, Alaska*. Ph.D. dissertation, Department of Geosciences, University of Tucson, Tucson.

Dixon, E. J., 1983. Pleistocene proboscidean fossils from the Alaskan continental shelf. *Quaternary Research*, **20**(1), 113–119.

Dixon, E. J., 1993. *Quest for the Origins of the First Americans*. Albuquerque: University of New Mexico Press.

Dixon, E. J., 1999. *Bones, Boats and Bison: Archeology and the First Colonization of Western North America*. Albuquerque: University of New Mexico Press.

Dixon, E. J., 2013. *Arrows and Atl Atls: A Guide to the Archeology of Beringia*. Washington, DC: National Park Service, Shared Beringian Heritage Program.

Dixon, E. J., Heaton, T. H., Fifield, T. E., Hamilton, T. D., Putnam, D. E., and Grady, F., 1997. Late Quaternary regional geoarchaeology of southeast Alaska karst: a progress report. *Geoarchaeology*, **12**(6), 689–712.

Dyke, A. S., Moore, A., and Robertson. L., 2003. *Deglaciation of North America.* Geological Survey of Canada Open File, 1574. Thirty-two digital maps at 1:7,000,000 scale with accompanying digital chronological database and one poster (2 sheets) with full map series.

Easton, N. A., McKay, G. R., Young, P. B., Schnurr, P., and Yesner, D. R., 2012. Chindadn in Canada? Emergent evidence of the Pleistocene transition in southeast Beringia as revealed by the Little John site, Yukon. In Goebel, T., and Buvit, I. (eds.), *From the Yenisei to the Yukon: Interpreting Lithic Assemblage Variability in Late Pleistocene/Early Holocene Beringia*. College Station: Texas A&M University Press, pp. 289–307.

Elias, S. A., and Crocker, B., 2008. The Bering Land Bridge: a moisture barrier to the dispersal of steppe-tundra biota? *Quaternary Science Reviews*, **27**(27–28), 2473–2483.

Elias, S. A., Short, S. K., Nelson, C. H., and Birks, H. H., 1996. Life and times of the Bering Land Bridge. *Nature*, **382**(6586), 60–63.

Elias, S. A., Short, S. K., and Birks, H. H., 1997. Late Wisconsin environments of the Bering Land Bridge. *Paleogeography, Palaeoclimatology, Paleoecology*, **136**(1–4), 293–308.

Elias, S. A., Berman, D., and Alfimov, A., 2000. Late Pleistocene beetle faunas of Beringia: where east met west. *Journal of Biogeography*, **27**(6), 1349–1363.

Fedje, D., Mackie, Q., Smith, N., and McLaren, D., 2011. Function, visibility, and interpretation of archaeological assemblages at the Pleistocene/Holocene transition in Haida Gwaii. In Goebel, T., and Buvit, I. (eds.), *From the Yenisei to the Yukon: Interpreting Lithic Assemblage Variability in Late Pleistocene/Early Holocene Beringia*. College Station: Texas A&M University Press, pp. 323–342.

Froese, D. G., Zazula, G. D., Westgate, J. A., Preece, S. J., Sanborn, P. T., Reyes, A. V., and Pearce, N. J. G., 2009. The Klondike goldfields and Pleistocene environments of Beringia. *GSA Today*, **19**(8), 4–10.

Giddings, J. L., 1964. *The Archaeology of Cape Denbigh*. Providence: Brown University Press.

Goebel, T., 1999. Pleistocene human colonization of Siberia and peopling of the Americas: an ecological approach. *Evolutionary Anthropology*, **8**(6), 208–227.

Goebel, T., 2002. The "microblade adaptation" and recolonization of Siberia during the late Upper Pleistocene. In Elston, R. G., and Kuhn, S. L. (eds.), *Thinking Small: Global Perspective on Microlithization*. Alexandria: American Anthropological Association. Archeological Papers of the American Anthropological Association, Vol. 12, pp. 117–131.

Goebel, T., Powers, W. R., and Bigelow, N. H., 1991. The Nenana complex of Alaska and Clovis origins. In Bonnichsen, R., and Turnmire, K. L. (eds.), *Clovis: Origins and Adaptations*. Corvallis: Center for the Study of the First Americans, Oregon State University, pp. 49–79.

Goebel, T., Waters, M. R., and O'Rourke, D. H., 2008. The late Pleistocene dispersal of modern humans in the Americas. *Science*, **319**(5869), 1497–1502.

Goebel, T., Smith, H. L., DiPietro, L., Waters, M. R., Hockett, B., Graf, K. E., Gal, R., Slobodin, S. B., Speakman, R. J., Driese, S. G., and Rhode, D., 2013. Serpentine Hot Springs, Alaska: results of excavations and implications for the age and significance of northern fluted points. *Journal of Archaeological Science*, **40**(12), 4222–4233.

Guthrie, R. D., 1968. Paleoecology of the large-mammal community in interior Alaska during the late Pleistocene. *The American Midland Naturalist,* **79**(2):346–363.

Guthrie, R. D., 1982. Mammals of the Mammoth Steppe as paleoenvironmental indicators. In Hopkins, D. M., Matthews, J. V., Jr., Schweger, C. E., and Young, S. B. (eds.), *Paleoecology of Beringia*. New York: Academic, pp. 307–326.

Guthrie, R. D., 1984. Mosaics, allelochemics, and nutrients: an ecological theory of late Pleistocene megafaunal extinctions. In Martin, P. S., and Klein, R. G. (eds.), *Quaternary Extinctions: A Prehistoric Revolution*. Tucson: University of Arizona Press, pp. 259–298.

Guthrie, R. D., 1990. *Frozen Fauna of the Mammoth Steppe: The Story of Blue Babe*. Chicago: University of Chicago Press.

Guthrie, R. D., 2001. Origin and causes of the Mammoth Steppe: a story of cloud cover, woolly mammal tooth pits, buckles, and inside-out Beringia. *Quaternary Science Reviews*, **20**(1–3), 549–574.

Guthrie, R. D., 2006. New carbon dates link climatic change with human colonization and Pleistocene extinctions. *Nature*, **441**(7090), 207–209.

Heaton, T. H., and Grady, F., 2003. The late Wisconsin vertebrate history of Prince of Wales Island, southeast Alaska. In Schubert, B. W., Mead, J. I., and Graham, R. W. (eds.), *Ice Age Cave Faunas of North America*. Bloomington: Indiana University Press, pp. 17–53.

Hoffecker, J. F., and Elias, S. A., 2007. *Human Ecology of Beringia*. New York: Columbia University Press.

Höfle, C., Edwards, M. E., Hopkins, D. M., Mann, D. H., and Ping, C.-L., 2000. The full-glacial environment of the northern Seward Peninsula, Alaska, reconstructed from the 21,500-year-old Kitluk paleosol. *Quaternary Research*, **53**(2), 143–153.

Holmes, C. E., 1996. Broken Mammoth. In West, F. H. (ed.), *American Beginnings: The Prehistory and Palaeoecology of Beringia.* Chicago: University of Chicago Press, pp. 312–317.

Holmes, C. E., 2001. Tanana River Valley archaeology circa 14,000 to 9000 B.P. *Arctic Anthropology*, **38**(2), 154–170.

Holmes, C. E., 2011. The Beringian and transitional periods in Alaska: technology of the east Beringian tradition as viewed from Swan Point. In Goebel, T., and Buvit, I. (eds.), *From the Yenisei to the Yukon: Interpreting Lithic Assemblage Variability in Late Pleistocene/Early Holocene Beringia*. College Station: Texas A&M University Press, pp. 179–191.

Hopkins, D. M., 1959. Cenozoic history of the Bering Land Bridge. *Science*, **129**(3362), 1519–1528.

Hopkins, D. M., 1967. *The Bering Land Bridge*. Stanford: Stanford University Press.

Hopkins, D. M., 1982. Aspects of the paleogeography of Beringia during the late Pleistocene. In Hopkins, D. M., Matthews, J. V., Jr., Schweger, C. E., and Young, S. B. (eds.), *Paleoecology of Beringia*. New York: Academic, pp. 3–28.

Hopkins, D. M., Matthews, J. V., Jr., Schweger, C. E., and Young, S. B. (eds.), 1982. *Paleoecology of Beringia*. New York: Academic.

Hultén, E., 1968. *Flora of Alaska and Neighboring Territories; A Manual of the Vascular Plants*. Stanford: Stanford University Press.

Huntley, D. J., and Richards, M. P., 1997. The age of the Diring Yuriakh archaeological site. *Ancient TL*, **15**(2–3), 48–49.

Kaufman, D. S., Ager, T. A., Anderson, N. J., Anderson, P. M., Andrews, J. T., Bartlein, P. J., Brubaker, L. B., Coats, L. L., Cwynar, L. C., Duvall, M. L., Dyke, A. S., Edwards, M. E., Eisner, W. R., Gajewski, K., Geirsdóttir, A., Hu, F. S., Jennings, A. E., Kaplan, M. R., Kerwin, M. W., Lozhkin, A. V., MacDonald, G. M., Miller, G. H., Mock, C. J., Oswald, W. W., Otto-Bliesner, B. L., Porinchu, D. F., Rühland, K., Smol, J. P., Steig, E. J., and Wolfe, B. B., 2004. Holocene thermal maximum in the western Arctic (0–180° W). *Quaternary Science Reviews*, **23**(5–6), 529–560.

Kokorowski, H. D., Anderson, P. M., Mock, C. J., and Lozhkin, A. V., 2008. A re-evaluation and spatial analysis of evidence for a Younger Dryas climatic reversal in Beringia. *Quaternary Science Reviews*, **27**(17–18), 1710–1722.

Kuzmin, Y. V., 2008. Siberia at the Last Glacial Maximum: environment and archaeology. *Journal of Archaeological Research*, **16**(2), 163–221.

Kuzmin, Y. V., and Keates, S. G., 2005. Dates are not just data: Paleolithic settlement patterns in Siberia derived from radiocarbon records. *American Antiquity*, **70**(4), 773–789.

Larsen, H., 1968. *Trail Creek: Final Report on the Excavation of Two Caves on Seward Peninsula, Alaska*. København: Ejnar Munksgaard. Acta Arctica, Vol. 15.

Manley, W. F., 2002. *Postglacial Flooding of the Bering Land Bridge: A Geospatial Animation*. Boulder: INSTAAR, University of Colorado, Vol. 1. Electronic data available at http://instaar.colorado.edu/QGISL/bering_land_bridge/.

Mann, D. H., Peteet, D. M., Reanier, R. E., and Kunz, M. L., 2002. Responses of an Arctic landscape to Lateglacial and early Holocene climatic changes: the importance of moisture. *Quaternary Science Reviews*, **21**(8–9), 997–1021.

Mann, D. H., Groves, P., Kunz, M. L., Reanier, R. E., and Gaglioti, B. V., 2013. Ice-age megafauna in Arctic Alaska: extinction, invasion, survival. *Quaternary Science Reviews*, **70**, 91–108.

Mason, O. K., and Jordan, J. W., 1993. Heightened north Pacific storminess during synchronous late Holocene erosion of northwest Alaska beach ridges. *Quaternary Research*, **40**(1), 55–69.

Mason, O. K.,Neal, W. J., and Pilkey, O. H.,1997. *Living with the Coast of Alaska*. Duke Durham: University Press.

Meiri, M., Lister, A. M., Collins, M. J., Tuross, N., Goebel, T., Blockley, S., Zazula, G. D., van Doorn, N., Guthrie, R. D., Boeskorov, G. G., Baryshnikov, G. F., Sher, A., and Barnes, I., 2014. Faunal record identifies Bering isthmus conditions as constraint to end-Pleistocene migration to the New World. *Proceedings of the Royal Society B*, **281**(1776), 2013–2167.

Misarti, N., Finney, B. P., Jordan, J. W., Maschner, H. D. G., Addison, J. A., Shapley, M. D., Krumhardt, A., and Begét, J. E., 2012. Early retreat of the Alaska Peninsula Glacier Complex and the implications for coastal migrations of First Americans. *Quaternary Science Reviews*, **48**, 1–6.

Mobley, C. M., 1991. *The Campus Site: A Prehistoric Camp at Fairbanks, Alaska*. Fairbanks: University of Alaska Press.

Mochanov, Y. A., and Fedoseeva, S. A., 1996. Aldansk: Aldan river valley, Sakha Republic. In West, F. H. (ed.), *American Beginnings: The Prehistory and Palaeoecology of Beringia*. Chicago: University of Chicago Press, pp. 157–214.

Muhs, D. R., Ager, T. A., Been, J. M., Rosenbaum, J. G., and Reynolds, R. L., 2000. An evaluation of methods for identifying and interpreting buried soils in late Quaternary loess in Alaska. In Kelley, K. D., and Gough, L. P. (eds.), *Geological Studies in Alaska by the U.S. Geological Survey, 1998*. Denver: U.S. Geological Survey. U.S. Geological Survey Professional Paper 1615, pp. 127–146.

Nikolskiy, P. A., and Pitulko, V. V., 2013. Evidence from the Yana Palaeolithic site, Arctic Siberia, yields clues to the riddle of

mammoth hunting. *Journal of Archaeological Science*, **40**(12), 4189–4197.
Nikolskiy, P. A., Basilyan, A. E., Sulerzhitsky, L. D., and Pitulko, V. V., 2010. Prelude to extinction: revision of the Achchagyi-Allaikha and Berelyokh mass accumulations of mammoth. *Quaternary International*, **219**(1–2), 16–25.
Odess, D. P., and Rasic, J. T., 2007. Toolkit composition and assemblage variability: the implications of Nogahabara I, northern Alaska. *American Antiquity*, **72**(4), 691–717.
Péwé, T. L., 1965 (reprinted 1977). Middle Tanana River Valley. In Péwé, T. L., Ferrains, O. J., Jr., Nichols, D. R., and Karlstrom, T. N. V. (eds.), *International Association for Quaternary Research, VIIth Congress. Guide Book for Field Conference F: Central and South-Central Alaska*. College: Division of Geological and Geophysical Surveys, Department of Natural Resources, pp. 36–54.
Péwé, T. L., 1975. *Quaternary Geology of Alaska*. Washington, DC: United States Government Printing Office. U.S. Geological Survey Professional Paper 835.
Péwé, T. L., 1977. Middle Tanana River Valley. In Péwé, T. L., Ferrains, O. J., Nichols, D. R., and Karlstrom, T. N. V. (eds.), *Guide to the Quaternary Geology: Central and South-Central Alaska*. College, Alaska: Division of Geological and Geophysical Surveys, Department of Natural Resources, pp. 36–54.
Pitulko, V. V., Nikolsky, P. A., Girya, E. Y., Basilyan, A. E., Tumskoy, V. E., Koulakov, S. A., Astakhov, S. N., Pavlova, E. Y., and Anisimov, M. A., 2004. The Yana RHS site: humans in the Arctic before the Last Glacial Maximum. *Science*, **303**(5654), 52–56.
Potter, B. A., 2005. *Site Structure and Organization in Central Alaska: Archaeological Investigations at Gerstle River.* Ph.D. dissertation, Department of Anthropology, University of Alaska, Fairbanks.
Potter, B. A., 2008. Radiocarbon chronology of central Alaska: technological continuity and economic change. *Radiocarbon*, **50**(2), 181–204.
Potter, B. A., 2011. Late Pleistocene and early Holocene assemblage variability in central Alaska. In Goebel, T., and Buvit, I. (eds.), *From the Yenisei to the Yukon: Interpreting Lithic Assemblage Variability in Late Pleistocene/Early Holocene Beringia*. College Station: Texas A&M University Press, pp. 215–233.
Potter, B. A., Irish, J. D., Reuther, J. D., Gelvin-Reymiller, C., and Holliday, V. T., 2011. A Paleoindian child cremation and residential structure from eastern Beringia. *Science*, **311**(6020), 1058–1062.
Potter, B. A., Holmes, C. E., and Yesner, D. R., 2013. Technology and economy among the earliest prehistoric foragers in interior eastern Beringia. In Graf, K. E., Ketron, C. V., and Waters, M. R. (eds.), *Paleoamerican Odyssey*. College Station: Center for the Study of the First Americans, Texas A&M University, pp. 81–104.
Potter, B. A., Irish, J. D., Reuther, J. D., and McKinney, H. J., 2014. New insights into eastern Beringian mortuary behavior: a terminal Pleistocene double infant burial at Upward Sun River. *Proceedings of the National Academy of Sciences*, **111**(48), 17060–17065.
Powers, W. R., and Hoffecker, J. F., 1989. Late Pleistocene settlement in the Nenana Valley, central Alaska. *American Antiquity*, **54**(2), 263–287.
Rasic, J. T., 2011. Functional variability in the late Pleistocene archaeological record of eastern Beringia: a model of late Pleistocene land use and technology from northwest Alaska. In Goebel, T., and Buvit, I. (eds.), *From the Yenisei to the Yukon: Interpreting Lithic Assemblage Variability in Late Pleistocene/Early Holocene Beringia*. College Station: Texas A&M University Press, pp. 128–164.
Reanier, R. E., 1982. An application of pedological and palynological techniques at the Mesa site, northern Brooks Range, Alaska. *Anthropological Papers of the University of Alaska*, **20**(1–2), 123–139.
Reanier, R. E., 1995. The antiquity of Paleoindian materials in northern Alaska. *Arctic Anthropology*, **32**(1), 31–50.
Reger, R. D., Stevens, D. S. P., and Solie, D. N., 2008. *Surficial Geology of the Alaska Highway Corridor, Delta Junction to Dot Lake, Alaska*. Fairbanks: Division of Geological and Geophysical Surveys.
Reuther, J. D., 2013. *Late Glacial and Early Holocene Geoarchaeology and Terrestrial Paleoecology in the Lowlands of the Middle Tanana Valley, Subarctic Alaska.* Ph.D. dissertation, University of Arizona, Tucson.
Sattler, R., Vinson, D. M., and Gillispie, T. E., 2001. Calibrated radiocarbon ages and taphonomic factors in Beringian cave faunas at the end of the Pleistocene. In Gerlach, S. C., and Murray, M. S. (eds.), *People and Wildlife in Northern North America: Essays in Honor of R. Dale Guthrie*. Oxford: Archaeopress. British Archaeological Reports, International Series, Vol. 944, pp. 112–123.
Shuman, B., and Finney, B., 2007. Lake level studies/North America. In Elias, S. A. (ed.), *Encyclopedia of Quaternary Science*. Amsterdam: Elsevier, pp. 1374–1383.
Slobodin, S., 1999. Northeast Asia in the late Pleistocene and early Holocene. *World Archaeology*, **30**(3), 484–502.
Smith, H. L., Rasic, J. T., and Goebel, T., 2013. Biface traditions of northern Alaska and their role in the peopling of the Americas. In Graf, K. E., Ketron, C. V., and Waters, M. R. (eds.), *Paleoamerican Odyssey.* College Station: Center for the Study of the First Americans, Texas A&M University, pp. 105–123.
Ten Brink, N. W., and Waythomas, C. F., 1985. Late Wisconsin glacial chronology of the north-central Alaska Range: a regional synthesis and its implications for early human settlements. *National Geographic Research Reports*, **19**, 15–32.
Thorson, R. M., 1990. Geologic contexts of archaeological sites in Beringia. In Lasca, N. P., and Donahue, J. (eds.), *Archaeological Geology of North America*. Boulder: Geological Society of America. Centennial Special volume 4, pp. 399–420.
Thorson, R. M., and Hamilton, T. D., 1977. Geology of the dry creek site; a stratified early man site in interior Alaska. *Quaternary Research*, **7**(2), 149–176.
Tseitlin, S. M., 1979. *Geologiia paleolita Severnoi Azii [Geology of the Paleolithic of Northern Asia]*. Nauka: Moskva.
Ugolini, F. C., 1986. Pedogenic zonation in the well-drained soils of the Arctic regions. *Quaternary Research*, **26**(1), 100–120.
Ukraintseva, V. V., Agenbroad, L. D., and Mead, J. I., 1996. A palaeoenvironmental reconstruction of the "Mammoth Epoch" of Siberia. In West, F. H. (ed.), *American Beginnings: The Prehistory and Palaeoecology of Beringia*. Chicago: University of Chicago Press, pp. 129–136.
Vasil'ev, S. A., 1993. The upper Palaeolithic of northern Asia. *Current Anthropology*, **34**(1), 82–92.
Waters, M. R., Forman, S. L., and Pierson, J. M., 1999. Late Quaternary geology and geochronology of Diring Yuriakh, an Early Paleolithic site in Central Siberia. *Quaternary Research*, **51**(2), 195–211.
West, F. H., 1967. The Donnelly Ridge site and the definition of an early core and blade complex in central Alaska. *American Antiquity*, **32**(3), 360–382.
West, F. H., 1975. Dating the Denali Complex. *Arctic Anthropology*, **12**(1), 76–81.
West, F. H., 1981. *The Archaeology of Beringia*. New York: Columbia University Press.
West, F. H. (ed.), 1996. *American Beginnings: The Prehistory and Palaeoecology of Beringia*. Chicago: University of Chicago Press.

West, F. H., Robinson, B. S., and Curran, M. L., 1996. Phipps site. In West, F. H. (ed.), *American Beginnings: The Prehistory and Palaeoecology of Beringia*. Chicago: University of Chicago Press, pp. 381–386.

Wygal, B. T., 2010. Prehistoric upland tool production in the central Alaska Range. *Alaska Journal of Anthropology*, **8**(1), 107–119.

Yesner, D. R., 1989. Moose hunters of the boreal forest? A re-examination of subsistence patterns in the western subarctic. *Arctic*, **42**(2), 97–108.

Yesner, D. R., 2007. Faunal extinction, hunter-gatherer foraging strategies, and subsistence diversity among eastern Beringian Paleoindians. In Walker, R. B., and Driskell, B. N. (eds.), *Foragers of the Terminal Pleistocene in North America*. Lincoln: University of Nebraska Press, pp. 15–31.

Yi, S., and Clark, G., 1985. The "Dyuktai Culture" and New World origins. *Current Anthropology*, **26**(1), 1–20.

Zazula, G. D., Schweger, C. E., Beaudoin, A. B., and McCourt, G. H., 2006. Macrofossil and pollen evidence for full-glacial steppe with an ecological mosaic along the Bluefish River, eastern Beringia. *Quaternary International*, **142–143**, 2–19.

BIG EDDY SITE, MISSOURI

Edwin R. Hajic
GeoArc Research, Inc., Santa Fe, NM, USA

The Big Eddy site (23CE426) is located in the lower Sac River valley at the Plains-Eastern Woodlands boundary in southwest Missouri, USA (Hajic et al., 2007). It is a rare, documented site that contains distinctly stratified and radiocarbon-dated Early Paleoindian through Late Archaic cultural deposits. Early projectile points recovered from excavations at the site include Gainey, Sedgwick (Eastern Folsom), Dalton, and San Patrice (Hope and St. Johns varieties) (Lopinot et al., 1998, 2000). There is a scant and inconclusive evidence for a pre-Early Paleoindian cultural horizon, represented by a large possibly utilized flake, refit fragments of a possible anvilstone, and a poorly preserved bison-sized bone fragment.

Early cultural material is contained within alluvial deposits belonging to an early submember of the Rodgers Shelter Member (a series of alluvial fills) that span the metamorphosis from a braided to meandering regime in the Sac River valley. Alluvium in the lower and middle part of the early submember aggraded between ca. 15,300 and 13,250 cal year BP through a transition from braid-bar to upper point bar depositional environment at the site. Pre-Paleoindian-age material is contained in at least the uppermost 0.7 m of this sequence. Alluvium in the middle and upper part of the early submember that hosts the Paleoindian sequence is 0.7 m thick and aggraded between ca. 13,250 and 11,870 cal year BP through the transition from point bar to floodplain depositional environment. A complex buried soil altered deposits with Paleoindian and pre-Paleoindian material. The buried soil has a cumulic A horizon and is welded onto a paleogeomorphic surface at the top of Middle Paleoindian material that stabilized during the Younger Dryas (Hajic et al., 2007; Dorale et al., 2010).

Nearly 3 m of fine-grained floodplain alluvium, with a basal age of about 11,250 cal year BP, buries and preserves the Paleoindian record, and it contains stratified cultural material representing nearly the entire post-Paleoindian prehistoric cultural sequence as well. Post-Paleoindian alluvial stratification at the site resulted from lateral migration of the stream and aggradation of thick floodplain overbank and terrace veneer deposits of Early and Middle Holocene age, as well as a thin terrace veneer deposit of Late Holocene age at the top of the section. Overlying deposits are thick enough to mask completely the relief characterizing the buried Paleoindian alluvial landscape. At least seven distinctly stratified Early Archaic components are represented within the middle submember, including Breckenridge, Scottsbluff, Cache River, Graham Cave, Rice Lobed, and Hidden Valley. At least five later Archaic components are represented in both floodplain and terrace veneer deposits in different spatial locations at differing depths in association with a younger buried soil developed in the top of the middle submember. Minor Woodland and Mississippian components are within the uppermost increment of the late submember terrace veneer that is altered by the surface soil.

Big Eddy may not be a unique locality but rather part of a Paleoindian district in the lower Sac River valley. A cutbank survey along the steep eroding face of the river identified 22 Paleoindian sites, including at least one Clovis site, along 49 km of the lower Sac River (Ray and Lopinot, 2005). Valley geomorphic mapping and cutbank stratigraphy suggest other Paleoindian sites are likely associated with paleotopographic highs at the tops of former braid bars.

For further reading, see Lopinot and Ray (2007, 2010), Lopinot et al. (1998, 2000, 2005), and Ray et al. (1998, 2000, 2009) including papers within.

Bibliography

Dorale, J. A., Wozniak, L. A., Bettis, E. A., III, Carpenter, S. J., Mandel, R. D., Hajic, E. R., Lopinot, N. H., and Ray, J. H., 2010. Isotopic evidence for Younger Dryas aridity in the North American midcontinent. *Geology*, **38**(6), 519–522.

Hajic, E. R., Mandel, R. D., Ray, J. H., and Lopinot, N. H., 2007. Geoarchaeology of stratified Paleoindian deposits at the Big Eddy site, southwest Missouri, U.S.A. *Geoarchaeology*, **22**(8), 891–934.

Lopinot, N. H., and Ray, J. H., 2007. Trampling experiments in the search for the earliest Americans. *American Antiquity*, **72**(4), 771–782.

Lopinot, N. H., and Ray, J. H., 2010. Late Paleoindian interaction and exchange at the Big Eddy site in southwest Missouri. In Hurst, S., and Hofman, J. L. (eds.), *Exploring Variability in Early Holocene Hunter-Gatherer Lifeways*. Lawrence: Department of Anthropology, University of Kansas, pp. 119–134. Publications in Anthropology 25.

Lopinot, N. H., Ray, J. H., and Conner, M. D. (eds.), 1998. *The 1997 Excavations at the Big Eddy Site (23CE426) in Southwest Missouri*. Springfield: Center for Archaeological Research, Southwest Missouri State University. Special Publication, 2.

Lopinot, N. H., Ray, J. H., and Conner, M. D. (eds.), 2000. *The 1999 Excavations at the Big Eddy Site (23CE426)*. Springfield: Center for Archaeological Research, Southwest Missouri State University. Special Publication, 3.

Lopinot, N. H., Ray, J. H., and Conner, M. D. (eds.), 2005. *Regional Research and the Archaic Record at the Big Eddy Site (23CE426), Southwest Missouri*. Springfield: Center for Archaeological Research, Southwest Missouri State University. Special Publication, 4.

Ray, J. H., and Lopinot, N. H., 2005. Cutbank survey. In Lopinot, N. H., Ray, J. H., and Conner, M. D. (eds.), *Regional Research and the Archaic Record at the Big Eddy Site (23CE426), Southwest Missouri*. Springfield: Center for Archaeological Research, Southwest Missouri State University. Special Publication, 4, pp. 38–102.

Ray, J. H., Lopinot, N. H., Hajic, E. R., and Mandel, R. D., 1998. The Big Eddy site: a multicomponent Paleoindian site on the Ozark border, southwest Missouri. *Plains Anthropologist*, **43**(163), 73–81.

Ray, J. H., Lopinot, N. H., Hajic, E. R., and Mandel, R. D., 2000. Possible pre-Clovis-age artifacts from the Big Eddy site. *Current Research in the Pleistocene*, **17**, 68–71.

Ray, J. H., Lopinot, N. H., and Hajic, E. R., 2009. Archaic prehistory of the Western Ozarks of Southwest Missouri. In Emerson, T. E., McElrath, D. L., and Fortier, A. C. (eds.), *Archaic Societies: Diversity and Complexity Across the Midcontinent*. Albany: State University of New York Press, pp. 155–197.

BLOMBOS CAVE

Magnus M. Haaland and Christopher S. Henshilwood
Department of Archaeology, History, Cultural Studies and Religion, University of Bergen, Bergen, Norway

Blombos Cave is located in Blombosfontein Nature Reserve on the southern Cape coastline of South Africa. The site is situated within a south-facing cliff on the upper part of a coastal slope, ca. 34.5 m above sea level, some 100 m from the present-day shoreline. The cave formed at the base of the sandy limestone bed of the Wankoe Formation (Mio-/Pliocene aeolianites) at its contact with the underlying Table Mountain Group (quartzitic Ordovician sandstones).

The outer talus is stabilized by large, semi-exposed blocks and presents a gently sloping platform that extends 4–5 m southward. The cave interior comprises a main chamber with an accessible surface area of ca. 40 m^2. Irregular cavities and smaller interconnected channels and chambers extend inwardly. The sediments at the base of the cave contain detrital particles of the substratum which are most likely related to the disaggregation of the limestone during the initial stage of cave formation. The seaward extension of the original limestone bedrock was at one stage truncated by marine erosion sometime during the Plio-Pleistocene, resulting in the opening of the cave. Following this exposure, infill sediments from the cave exterior accumulated and intermixed with limestone roof spalls.

In the excavated part of the cave, near the cave entrance, the sedimentary sequence is more than 3 m deep. It contains a well-stratified and unconsolidated deposit that is characterized by three major lithostratigraphic units. At the base is a layered and finely laminated sequence that contains Middle Stone Age (MSA) artifacts and anthropogenic material. In the middle, there is a coarse, sandy horizon representing an occupational hiatus, and on top lies a thin, silty, and sandy deposit that contains Later Stone Age (LSA) material. The hiatus, which can be found over more than 95 % of the excavated area, shows no major disturbance from the overlaying LSA deposit (Henshilwood, 2005). Decomposed marine and terrestrial faunal remains (fish, shellfish, and animal bones) and organic material are found within the sandy LSA and MSA layers. Larger combustion features, smaller hearths, and ash-rich horizons are also observed throughout the sequence.

The MSA sequence in Blombos Cave has been dated to ca. 101–70 ka using a number of methods, including thermoluminescence (TL), optically stimulated luminescence (OSL), uranium-thorium series (U/Th), and electron spin resonance (ESR). The occupational hiatus between 70 and 2 ka suggests that the cave was sealed off by aeolian dune sand during this period. The cave entrance may have reopened during the mid-Holocene transgression (ca. 4–3 ka), when high sea levels eroded away most of the nearby sand dune. Remnants of this eroded dune system are still visible in the surrounding coastal landscape. The LSA sequence is radiocarbon dated to 2000–290 years BP.

The most informative archaeological material – some of it ascribed to the Still Bay techno-complex – has been recovered from the MSA sequence and includes worked and engraved ocher, ocher processing kits, engraved bone, marine shell beads, polished bone tools, and bifacially worked stone tools (Henshilwood et al., 2002, 2004; Mourre et al., 2010; Henshilwood et al., 2011). The archaeological material recovered from Blombos Cave shows that, during the MSA, humans had developed a diverse set of subsistence and procurement strategies and were regularly manufacturing composite tools. The evidence for personal ornaments and abstract depictions represents some of the earliest occurrences of symbolically mediated behavior. The MSA sequence at Blombos Cave is thus central to our current understanding

Boxgrove, Figure 1 Panoramic view of Blombos Cave interior (Photo by Magnus M. Haaland).

of the behavioral, cognitive, and cultural development of early humans in southern Africa during the Late Pleistocene (Figure 1).

Bibliography

Henshilwood, C. S., 2005. Stratigraphic integrity of the middle stone age levels at Blombos Cave. In d'Errico, F., and Backwell, L. (eds.), *From Tools to Symbols: From Early Hominids to Modern Humans; in Honour of Professor Phillip V. Tobias*. Johannesburg: Witwatersrand University Press, pp. 441–458.

Henshilwood, C. S., d'Errico, F., Yates, R., Jacobs, Z., Tribolo, C., Duller, G. A. T., Mercier, N., Sealy, J. C., Valladas, H., Watts, I., and Wintle, A. G., 2002. Emergence of modern human behavior: middle stone age engravings from South Africa. *Science*, **295**(5558), 1278–1280.

Henshilwood, C., d'Errico, F., Vanhaeren, M., van Niekerk, K., and Jacobs, Z., 2004. Middle stone age shell beads from South Africa. *Science*, **304**(5669), 404.

Henshilwood, C. S., d'Errico, F., van Niekerk, K. L., Coquinot, Y., Jacobs, Z., Lauritzen, S.-E., Menu, M., and García-Moreno, R., 2011. A 100,000-year-old ochre-processing workshop at Blombos Cave, South Africa. *Science*, **334**(6053), 219–222.

Mourre, V., Villa, P., and Henshilwood, C. S., 2010. Early use of pressure flaking on lithic artifacts at Blombos Cave, South Africa. *Science*, **330**(6004), 659–662.

Cross-references

Electron Spin Resonance (ESR) in Archaeological Context
Optically Stimulated Luminescence (OSL) Dating
Pigments
U-Series Dating

BOXGROVE

Richard I. Macphail
Institute of Archaeology, University College London, London, UK

The Lower Paleolithic site of Boxgrove, West Sussex, UK, is located 12 km north of the present day coastline of the English Channel, in a buried early Middle Pleistocene landscape that extends 26 km from east to west (Roberts and Pope, 2013). The area has had a long history of geological and archaeological investigation dating back to the nineteenth century. The main excavations were carried out in two gravel quarries that covered a 1 km stretch of paleocoastline (Roberts and Parfitt, 1999). A tibia and two teeth, probably from *Homo heidelbergensis* (Stringer et al., 1998), were recovered from a depositional sequence of marine followed by terrestrial sediments that were rich in artifacts and faunal remains.

The sediments record a change from interglacial/temperate (MIS 13) to glacial/cool conditions (MIS 12). Three marine cycles were found, with the highest point of marine transgression recorded at 43.5 m above sea level. However, this height is attributable to post-depositional neo-tectonics rather than a true eustatic rise in sea level only. Terminal marine regression led to the deposition of intertidal silts (Unit 4a/b) over nearshore sands (Unit 3) laid down during the transgression phase. Current date estimates for the warm-phase hominin occupation range between 500 and 478 ka. The lowermost major hominin occupation occurred in Unit 4b, with examples of large animal (e.g., horse) butchery and Acheulian hand axe manufacture preserved within laminated silt and chalky clay intertidal mudflat sediments as indicated by invertebrate microfossils (foraminifera and ostracods). The most extensive occupation, however, is recorded in Unit 4c, where concentrations of worked flint occur within a thin (now only ~40 mm in places) Aquic Udifluvent soil (calcaric-alluvial soil) formed by terrestrial ripening (weathering) of the uppermost Unit 4b. This process involved decalcification and a loss of mass (some 20–30 % by weight), which possibly developed briefly over ~100 years. Very few micro-pedological features (burrows and small invertebrate excrements) are preserved, but those present are consistent with small mammal fauna (voles and moles). This soil and overlying organic bed Unit 5a have now been mapped by boreholes across some 13 km of the full 26 km extent of the paleolandscape, outside the original quarry site. The sediments record the silting up and terrestrial landscape evolution of a large Middle Pleistocene marine embayment (Roberts and Pope, 2013). Uniquely at Quarry 1, a probable spring-fed freshwater pond was formed by eroding through Units 4a/b down into Unit 3, the freshwater event being coeval with the formation of Unit 4c elsewhere. Numerous hand axes, abundant bones of large fauna such as extinct rhinoceros, and preserved hominin remains were found here in calcareous sediments (Roberts et al., 2015). Anomalous inundation then affected the whole site, forming microlaminated and often ferruginous Unit 5a that likely originated as a carr (waterlogged woodland) colonized by alder. One borehole near Slindon, 5 km to the east, found a Unit 5a, in which both enigmatic coarse broad-leaved wood charcoal and remarkable examples of preserved, albeit degraded, wood occur (Macphail et al., 2010). Upward, the sequence eventually becomes dominated by cool-phase sediments, but even these include instances of refitting artifact scatters, i.e., lithic flakes that conjoin, or refit, back into parts of their original core, thereby giving evidence of undisturbed occupation residue and not simply reworked material displaced from earlier occupations. Both an occupied interstadial (within Unit 8) and cool, humid soliflual deposits (Unit 11) are recorded.

Acknowledgments

Mark Roberts is thanked for his contribution to this summary.

Bibliography

Macphail, R. I., Allen, M. J., Crowther, J., Cruise, G. M., and Whittaker, J. E., 2010. Marine inundation: effects on archaeological features, materials, sediments and soils. *Quaternary International*, **214**(1–2), 44–55.

Roberts, M. B., and Parfitt, S. A., 1999. *Boxgrove. A Middle Pleistocene Hominid Site at Eartham Quarry, Boxgrove, West Sussex*. London: English Heritage.

Roberts, M. B., and Pope, M. I., 2013. *Mapping the Early Middle Pleistocene Deposits of the Slindon Formation across the Coastal Plain of West Sussex and Eastern Hampshire*. London: English Heritage.

Roberts, M. B., Pope, M. I., and Parfitt, S. A., 2015. *Boxgrove: An Early Middle Pleistocene Hominid Site at Eartham Quarry, Boxgrove, West Sussex. Excavations 1990–1996*. London: English Heritage.

Stringer, C. B., Trinkhaus, E., Roberts, M. B., Parfitt, S. A., and Macphail, R. I., 1998. The Middle Pleistocene human tibia from Boxgrove. *Journal of Human Evolution*, **34**(5), 509–547.

BUILT ENVIRONMENT

Joseph Schuldenrein
Geoarchaeology Research Associates, Yonkers, NY, USA

Synonyms

Cultural landscapes; Human-engineered cultural, social, and physical landscapes

Definition

The *built environment* refers to landscapes that are largely generated by people to sustain human activity. These settings include buildings, parks, and infrastructure facilities. They are viewed on a variety of scales ranging from neighborhoods to cities and surrounding municipalities that constitute "greater metropolitan areas." The archaeology of the built environment refers to the performance of survey, testing, and more extensive excavation of cultural or heritage resources. In the current age of sustainability, archaeology undertaken in urban settings assumes increased significance because space is confined, and the nearly continuous development intrudes upon older historic resources that represent actual archives of urban growth. Such intrusions are lateral, vertical, or both, and they impose complex stratigraphic disturbances upon remains that possess inherent archaeological importance. In fact, significant cultural resources are contained within the complicated accumulation of sediments laid down by natural and anthropogenic processes. These resources are subsequently disturbed or otherwise overridden by successive phases of development and landscaping.

There is a "top-down" bias in ranking the archaeological remains of the built environment. Traditional heuristic templates and theoretical models hold that stratified urban deposits assume increased importance with depth (i.e., age) and degree of preservation (i.e., retention of "archaeological integrity and context"). In the United States, for example, where the 50-year rule enacted under Section 106 of the National Historic Preservation Act (NHPA, 1966) determines the classification of a resource as formally significant (if it is older than 50 years), upper sediments in an urban sequence are considered to be "fill," or effectively undifferentiated depositional bodies. As the word "fill" implies, such sediments, with or without embedded cultural materials, are almost entirely dismissed out of hand archaeologically under the presumption that they carry no apparent worth other than functioning to level out a surface. However, older sediments, reconfigured for the same purpose as fill but 100–200 years earlier, may be deemed significant because they formed the foundation of a historic structure or municipal feature whose antiquity potentially affords it *archaeological significance*. The plethora of archaeological investigations in urban settings has called into question these traditional models, in step with the increasing acceptance of the concept of the *Anthropocene*, a "new human-dominated geological epoch" (Lewis and Maslin, 2015). This epoch is largely founded on the premise that human impacts account for the unique and dense deposits of an increasingly urbanized contemporary world. Within that context, it can be argued that the built environment will constitute a more prominent, even dominant, arena for archaeological exploration. For geoarchaeologists, today's land use patterns, and their present and evolving sedimentary and depositional contexts, are pivotal to the performance of "future archaeology." It follows that more sophisticated methods in geoarchaeology must be developed to analyze, for example, sediment bodies impacted by a broad range of anthropogenic inputs and residue disaggregation patterns that possess multiple origins, some never before encountered in the archaeological record.

Introduction

The built environment's boundaries and structural components are not easily charted geographically for a given metropolitan area. They will extend outward to suburban, exurban, and even rural areas in which support facilities for human activities have been constructed. This entry will consider modern built environments, but the analytical framework postulates that similar processes of anthropogenic construction and disturbance can be traced back in time to the earliest settlements comprising durable architecture. Modern infrastructure components considered here include the utility, supply, and distribution networks that allow built environments to function in maintaining contemporary lifeways. Major utilities encompass water and sewerage systems, electric and gas grids, fiber-optic lines, transportation networks, and energy facilities. A corollary to the function of the built environment is that the utilization of spaces by their occupying populations creates activity loci that record evidence of work and leisure time behaviors. Thus, this perspective of the built environment represents an anthropological approach to the continuity of patterned behavior. Its study implies that contemporary activities are the eventual archives of past human behavior as it will be seen in the future.

For archaeology, the built landscape may be viewed as composite and functional geographic settings wherein archaeology is performed – generally for legal and compliance purposes but also for research, the latter typically on a smaller scale. Archaeological work is legally mandated in settings that stand to be modified by construction and related activities. Firms contracting for these projects engage in what is called Cultural Resource Management (CRM), of which the charge is to mitigate the destruction of cultural remains, or remove them in a controlled, scientific manner, for the benefit of the citizenry. When development of these settings is undertaken, legally defined *adverse* effects may accrue to buried cultural resources (per NHPA, 1966). Accordingly, when project designs necessitate disturbances to lands that are both slated for development and funded by public monies, mitigation measures may be mandated by law. Empirically, this means that if (formally defined) *significant* archaeological resources are encountered, these must be documented, recovered, or bypassed depending upon projected impacts. It is stressed that decisions on mitigating impacts to cultural resources within the built environment require unique cooperative arrangements between regulators, stakeholders, developers, engineers, and planners, as well as the cultural resource teams implementing the work. Decision-making is driven by cost-benefit analyses and implemented by private contractors (e.g., for constructing housing complexes) and by public development agencies (e.g., for expanding subway lines). Ultimately, the performance of archaeology in urban settings must be meticulously coordinated by archaeological teams, construction engineers, and urban planners to guarantee that the activities of each do not delay or otherwise impede those of the other. Scheduling and use of space in these efforts is of paramount importance – see Carver (2013) for a discussion of logistics and planning in London's Crossrail project.

Geoarchaeologists are beginning to play a significant role in planning and applying mitigation strategies because of an increased emphasis on noninvasive data prospection and recovery in this "age of sustainability" (Brown et al., 2011). This approach is a practical result of limited accessibility (see below) to the urban substrate, which is packed with dense configurations of utilities as well as communication and resource networks.

The built environment in urban areas will typically preserve both discrete and disparate locations where much, if not all, of the surface and subsurface terrain has been previously disturbed, sometimes in the earlier historic past. Archaeological resources in such settings are often difficult to assess formally because, as noted above, sediment bodies currently classified as historically insignificant "fill" may extend to nineteenth- and eighteenth-century layers (or earlier) and thereby acquire increased importance because they bear on land use and discard practices of historic antiquity. Since these layers are often "stacked" (i.e., formally stratified), they effectively constitute successive occupations or multilevel archaeological sites. Paradoxically, while such buried pockets of cultural residues are dominated by "disturbance" activities that may compromise their archaeological integrity, the array of deposits and the artifacts within them preserve unique archaeological features (in the standard sense). Such deposits should not be dismissed as fill horizons since they represent historic practices that have changed through time. Moreover, deeper strata in the historic succession generally reflect lower-level "disturbances," since older technologies generally resulted in less disaggregation of primary occupation loci. One could contend, with reason, that systematic excavation of an urban footprint exposes strata within a single, multicomponent historic site, and that each and every horizon holds archaeological significance in documenting the evolution of the city.

Viewed from a contemporary perspective, in exurban and rural areas where less extensive and often shallower disturbance has taken place, elements of built environments may be anomalous and unique. Examples of limited impacts in rural areas are single-purpose constructions such as sewer lines and roadways. Rural areas are likely to have larger expanses of intact land, which may be more likely to contain undisturbed evidence for prehistoric cultural resources, while more urban tracts may preserve "palimpsests" or complex superpositions of archaeological remains representing occupations ranging from the prehistoric to historic. The upper limits of this time line extend to the subrecent and recent. Preliminary assessments of archaeological sensitivity are often the initial steps in the legal compliance process that provide both developers and cultural resource regulators with strategic guidelines for archaeological exploration. For geoarchaeologists, the key issues involve reconstructions of site formation processes indexed by chronologies. Such syntheses are often assembled by linking horizontally- and vertically-fragmentary natural stratigraphies with cultural residua that have often been displaced by earlier construction and secondary mobilization from their primary (in situ) activity areas. Stratigraphic taxonomies are critical for sequencing and codifying time-transgressive chronologies at historic sites. These may extend vertically from complex anthropogenic horizons (at the top of the sequence) to largely geogenic soils and sediments (at the bottom). At historic sites, and especially within the built environment, the "laws of superposition" become problematic and may require site-specific modification based on complex interfingerings of laterally- and vertically-compromised features and strata. The practitioner is advised to consult Harris (1989, Chaps. 5 and 6) as a baseline for developing an overarching sequence, in part grounded by the Harris Matrix.

When addressing issues attendant to the archaeology of the built environment, researchers must be focused on one of two specific objectives, both of which bear on geoarchaeological elements: (1) Is the goal to examine only targeted archaeological contexts beneath stratigraphic layers of extant and older (recent to subrecent) debris as probing proceeds through vestiges of present and former built environments? or (2) Must investigators concern themselves with vertical documentation of the entire stratigraphic complex of remains up through and including the time of interest? These questions are currently being framed by twenty-first-century archaeologists in conjunction with the general concern that even contemporary landfills and dumps – signature archaeological components of built environments – must be considered future archaeological features going forward. It can be argued, for example, that today's landfill sites and the processes that account for their accumulation reflect a technology and functional urban context that will provide clues for archaeologists of the twenty-second century; in short, they will help reconstruct the cultural lifeways of the present day. These questions characterize contemporary archaeological debate in conjunction with the controversial designation of the Anthropocene as a unique time-stratigraphic unit whose signature is the record of multiscalar events largely attributable to human interference.

In general, however, the focus of this entry is methodological, and concentrates on the first question: specifically the performance of archaeological work in complex, modern built environments. Here, the prevailing need is to extract maximum archaeological information in compromised (subsurface) stratigraphic contexts (although see the entry on "Dumps and Landfill" elsewhere in this volume).

Historic background

Updated concepts of the built environment have their roots in anthropological archaeology and were developed by scholars who explored the connection between environment and human behavior (Rapoport, 1990). In a broad sense, such theoretical foundations expand upon the theme of the symbiotic relationship between adaptive behaviors and changing landscapes, an idea initially pioneered by Karl Butzer (1964) and referenced as the "man/land relationship." The pace of landscape change accelerated in historic times, and patterns of cultural adaptation emerged in response to diverse landscape transformations that increasingly included humanly engineered physical geographic settings.

A recent review of heuristic trends in anthropological archaeology argued that one of the most pressing issues in twenty-first-century archaeology was to explore "...the ways in which the built environment, including the visible remnants of past settlements and monuments, has shaped patterns of culture change" (Rodning, 2010). Over the long term, the interdependence between the environment and culturally structured behavior systems provides for evolutionary changes in the human condition and accounts for the transition from foraging to farming, to cite just one pivotal example. Dynamic environmental zones are seen as accommodating different subsistence patterns, and, by extension, they can variously impact sociopolitical and economic systems. More recent scholarship implicitly links the built environment to the aforementioned Anthropocene (Lewis and Maslin, 2015) wherein the prevailing and accelerated impacts of human activity have left sedimentological and stratigraphic records attributed to products of both cultural activities and climate change (Ruddiman, 2013; Waters et al., 2014). Viewed through a human ecological lens, Butzer's "man/land relationship" has changed to a point where the evidence of that record is now dictated more by human impacts and less by landscape transformations generated by unimpeded ecological cycles.

A compelling case has been made that two dates, AD 1610 and AD 1964, should be considered as marking the beginning of the Anthropocene based on the global scale of such impacts – known as a Global Stratotype Section and Point, or GSSP (Lewis and Maslin, 2015, 173). In support of the earlier date, there is evidence (from the Greenland ice cores) that AD 1610 marked a low point in CO_2 emissions worldwide. The latter date (AD 1964) marks the initial global effects of ^{14}C peaks due to nuclear weapon detonation. Broader interpretations equate the onset of the Anthropocene to the immediate post-Pleistocene (ca. after 10,000 BP) and even turning points thereafter, based on expanding regionally derived patterns of cultural impact on landscapes. For example, both the Industrial Revolution and the expansion of Euroamerican culture within the New World have been invoked as changes that triggered the epoch (Nevle and Bird, 2008; Fischer-Kowalski et al., 2014). While the argument in support of a globally-based date for the Anthropocene is ongoing, and falls beyond the scope of this presentation, the concept of the built environment factors deeply into all considerations of archaeological practice in contemporary urban settings. It can be argued that once complex societies take root and city-states are functionally or structurally recognizable in the archaeological record, the built environment is effectively introduced. It constitutes a separate archaeological domain together with the methodological challenges attendant to maximizing systematic recovery and interpretive yield from that context. Accordingly, time ranges for the onset of the built environment can vary significantly, from the third millennium BC in the ancient Near East to the eighteenth- and even ninieteenth-century in many parts of contemporary North America. For present purposes, however, the use of the term should probably be confined to archaeological activities performed in and around urban centers where basal infrastructures are seen as the foundations of progressively more functional and efficient variants of those surviving at the tops of sequences in contemporary cities.

The need to understand the archaeology of the built environment is clear. Urban landscapes house archaeological records associated with prominent cultural remains and their distributions, and these remains increase in richness through time. On a global scale, dominant demographic shifts from rural- to urban-based lifeways strongly indicate that local and regional investigations exploring the dynamics and timing of such trends mirror the evolution of the urban human condition. Perhaps even more important is that when researchers infer advances in infrastructure technology (through material culture studies of the same), they are effectively in a position to help develop future urban planning strategies. The watchwords "the past is the key to the future" are nowhere more compelling than in urban centers in the age of sustainability, where the management of finite resources is key, and where the lessons of patterned urban growth are preserved in deep urban stratigraphies. The latter provide timelines, explanatory models of growth, and ultimately help furnish guidelines to assist planners in managing and calibrating urban growth without depleting limited resources.

For the geoarchaeologist, the built environment presents a vast array of quandaries. These vary from narrowing investigative efforts to target single components, expanding strategies to explain the broader processes of site formation, documenting burial and stratification of later archaeological components, or even articulating the characteristics of contemporary cover sediments (i.e., landfills) that would make them key to understanding future site formation trajectories under the 50-year rule. In most cases, development projects will center on delineated project footprints that will be exposed for limited duration, not to be exposed again in the short term. Within a CRM framework, formal research designs help structure investigations, but very often in the practice of excavation, and despite the limited size of the footprint, new finds are exposed often resulting in a restructuring of project objectives based on interim interpretations and the restricted access to stratigraphic sections. Experience shows that a range of evidentiary resources must be drawn upon when fieldwork is limited by access. To geoarchaeologists, this means that in-field strategies must focus on the exposures available at specific points in time and space. Models of site formation are then grounded on inductive and/or deductive projections of sequences based on background studies (i.e., landscape chronologies for prehistoric settings as well as maps and documented histories for historic components) and, of course, detailed microstratigraphies when these are available. A further corollary is that under most CRM and heritage-based protocols, the steps attendant to documentation and investigation center around a preference for preservation in place, and not disturbance. That said, the broader arena of the built environment is implicitly a disturbed context. The footprint of the planned impacts (i.e., apartment building complex, subway line, sewerage system) has already undergone initial vetting such that it is ultimately fixed and cannot be avoided, effectively rendering that footprint – and further disturbance to it – a foregone conclusion. In most cases, the archaeologist is called upon to salvage systematically the vestiges of features and intact components lying within the impact zone slated for development.

The archaeology of the built environment has risen to prominence over the past two decades for two main reasons: (1) climate change and new ideas emphasizing sustainability and (2) accelerated migrations to urban areas, often but not exclusively from Third World countries. In both cases, the need to reconfigure and modernize infrastructures has resulted in lateral expansion of city boundaries as well as pressure to reconfigure and expand existing urban facilities. In the case of the latter, ongoing updates to utility networks and transport systems (i.e., trains and highways) require episodic access to existing underground infrastructures and progressive disruptions to modern, historic, and even prehistoric geological and cultural sequences. In North America, a recent example is the "Big Dig" in Boston, a subsurface downtown highway expansion project where novel discoveries of early colonial architecture and land use were exposed (Lewis, 2001). In another example, an eighteenth-century sailing sloop was found in lower Manhattan (New York City) during construction for the Freedom Tower, a structure designed to replace the post-9/11 World Trade Center complex. A spate of books discussing the unique challenges confronting the practice of archaeology in North American cities has underscored the need to develop new methodological approaches in future urban excavations (e.g., Seasholes, 2003; Rothschild and diZerega Wall, 2014).

Globally, current high technology detection surveys and excavations associated with major transit projects have revamped the scale and scope of built environment research in unprecedented ways (see Hattam, 2015). In London, the long-standing Cross Rail project (Crossrail Project) has exposed deeply stratified geoarchaeological contexts for that city's human and landscape histories since the Upper Pleistocene. It has been uniquely informative for the record of the plague and the Great London Fire of 1666. In Istanbul, decade-long research at the site of a massive subway expansion has revealed one of the world's largest collections of Byzantine shipwrecks as well as burial structures and evidence of prehistoric activity. That work has revised the antiquity of the city's origins by 6000 years and has involved extensive cooperation in interdisciplinary work among underwater archaeologists and geologists (Perinçek, 2010; İstanbul Arkeoloji Müzeleri, 2012; Pulak et al., 2015). Since 2012, expansion of Rio de Janeiro's subway complex has produced one of the most telling treasure troves of seventeenth- to nineteenth-century trash from that city's aristocratic sector. In Rome, a Metro (railway) design project beneath the Piazza Venezia has disclosed a two-story cultural center built by Emperor Hadrian two millennia ago (Egidi et al., 2010). This discovery, together with evidence for farming complexes several kilometers outside of the former city center, attested to structural and economic relationships between the administrative center and exurban agricultural areas.

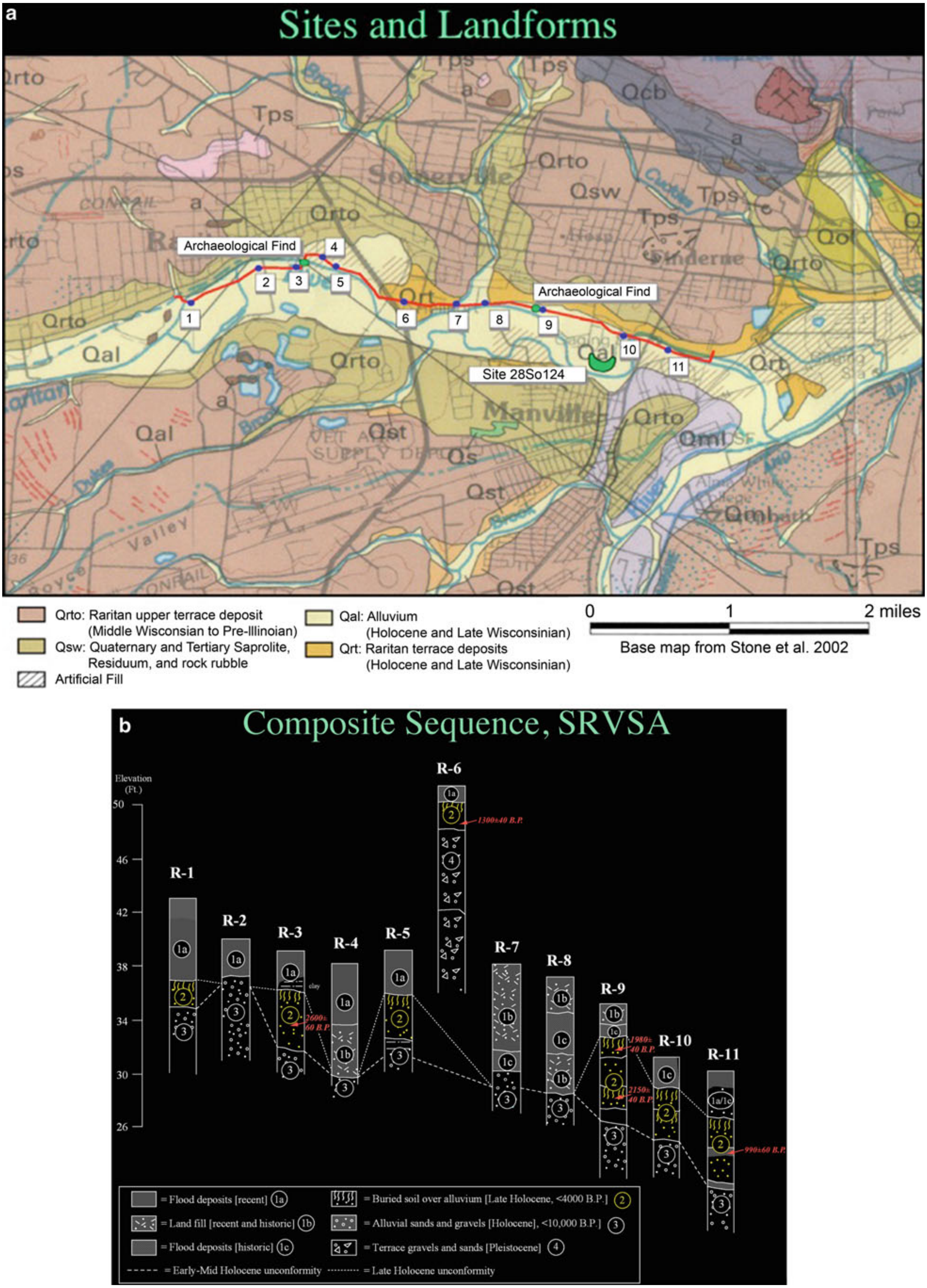
The nature of geoarchaeological exploration will vary depending on both the known archaeological potential of a location (based on previous exploration) and otherwise implicated potential. The latter refers to documented evidence of occupation or the presumption of such, either prehistoric or historic. Investigative methods and logistics are adjusted with respect to the origins and processes of subsurface disturbance, which may be broken down categorically according to developmental complexity. Categories range from minimal or single-source impacts in exurban to suburban locations to intensive and frequently multisource impacts in urban centers. Finally, levels of effort are formalized through memoranda of agreement (MOAs) dictated by planned impacts and agreed upon between developers, regulators, stakeholders, and the CRM teams with whom the geoarchaeologist coordinates in all phases of the endeavor.

Geoarchaeology in the exurban built environment (minimal disturbance)

Typically, exurban locales are affected by a single disturbance activity or several that are grouped together in order to minimize disruption and constrain construction footprints. The usual cases tend to include linear service routes such as pipeline corridors, water and sewer lines, and even roadways. Very often, such undertakings will not disturb laterally extensive swaths of land, and depths of disturbance may be shallow or minimal depending on the technologies applied for implementing construction. Construction of rights-of-way (ROWs) may also follow floodplains and river terraces, or parallel drainageways, as in the case of sewerage lines. Such settings are prime for containing stratified prehistoric sites.

For prehistoric projects in particular, it should be noted that landscape considerations factor significantly into research strategies. The geoarchaeologist will consult US Geological Survey (USGS) topographic maps to obtain broad guidelines for field relations – i.e., landforms and terrain gradients – and US Department of Agriculture (USDA)/Soil Conservation Service (SCS) county soil maps to obtain a preview of subsurface soil development, which provides a measure of subsurface stability along a floodplain. The latter is a predictor of prehistoric site preservation. For archaeological purposes, the question of buried soils is paramount. Equally significant are surficial geology maps, which present the distribution as well as the age of surface sediments. These maps are typically issued by state geological surveys and represent the collective mapping efforts of staff experts in regional Quaternary and bedrock geology. More recently LiDAR mapping has become available in many parts of North America, and such images enable researchers to discern landform and culturally based landscape disturbances beneath densely vegetated canopies or across otherwise obscured terrains. Expeditious application of map resources, together with a variety of historic documents and land use histories, provide the researcher with a preview of the antiquity and composition of the surface relations that his/her project is likely to encounter. Plans for systematic subsurface testing to locate cultural resources are refined on the strength of soil and sediment maps, their projected antiquity, and the known soil and landform associations of archaeological sites in the project area.

Figure 1a and b illustrates the application of this strategy to an extensive surface survey and subsurface testing



Built Environment, Figure 1 (Continued) program for a sewer line expansion project. The line spans a prehistorically sensitive terrace and more subtle alluvial features overlooking a tidal reach of the Raritan River in northern New Jersey. Simple shovel testing was deemed inappropriate by regulators because of obvious disturbance to upper deposits, which consisted of an undifferentiated organic fill clearly derived from localized swamp impoundments; the disturbed sediments were redistributed above an eroded soil cover (Schuldenrein, 2006). By superposing the footprint of the pipeline on the surface geology map (Stone et al., 2002), it was possible to identify areas of buried prehistoric potential that intersected with the line of impact. Sensitivity assessments were based on mapped distributions and ages of Late Quaternary deposits and landforms as well as the proximity of the line to a previously known archaeological site of Late Holocene age (Figure 1a).

The next step was systematic placement of geoprobe cores that ground-truthed the landform mapping units and isolated pristine alluvial deposits that were sampled for dating purposes (Figure 1b). Bulk organic determinations confirmed the age of the paleosol at < 4000 BP. It was possible to eliminate disturbed tracts from testing to confirm the antiquity of buried deposits corresponding to the known Late Archaic to Woodland occupations in the area, and to isolate the only intact buried segment of the landscape that could potentially preserve archaeological materials. The geoprobe sections were linked together across the length of the line, and they disclosed the prevalence of the paleosol (Bw horizon), albeit with pockets of disturbance (probably by land releveling activities along the western segment; Figure 1b). The fill-paleosol unconformity was the key to understanding the prominence of a buried but once stable surface. As a result of this testing, the sewer authority was able to determine if it wished to test for additional prehistoric site potential or to reroute a small segment of the line. They opted for the former, with the regulator's approval. The geoarchaeological survey and testing effort produced the baseline for a limited area-wide excavation that was both scientifically sound and cost effective (Schuldenrein, 2006).

Geoarchaeology of the urban built environment (significant disturbance)

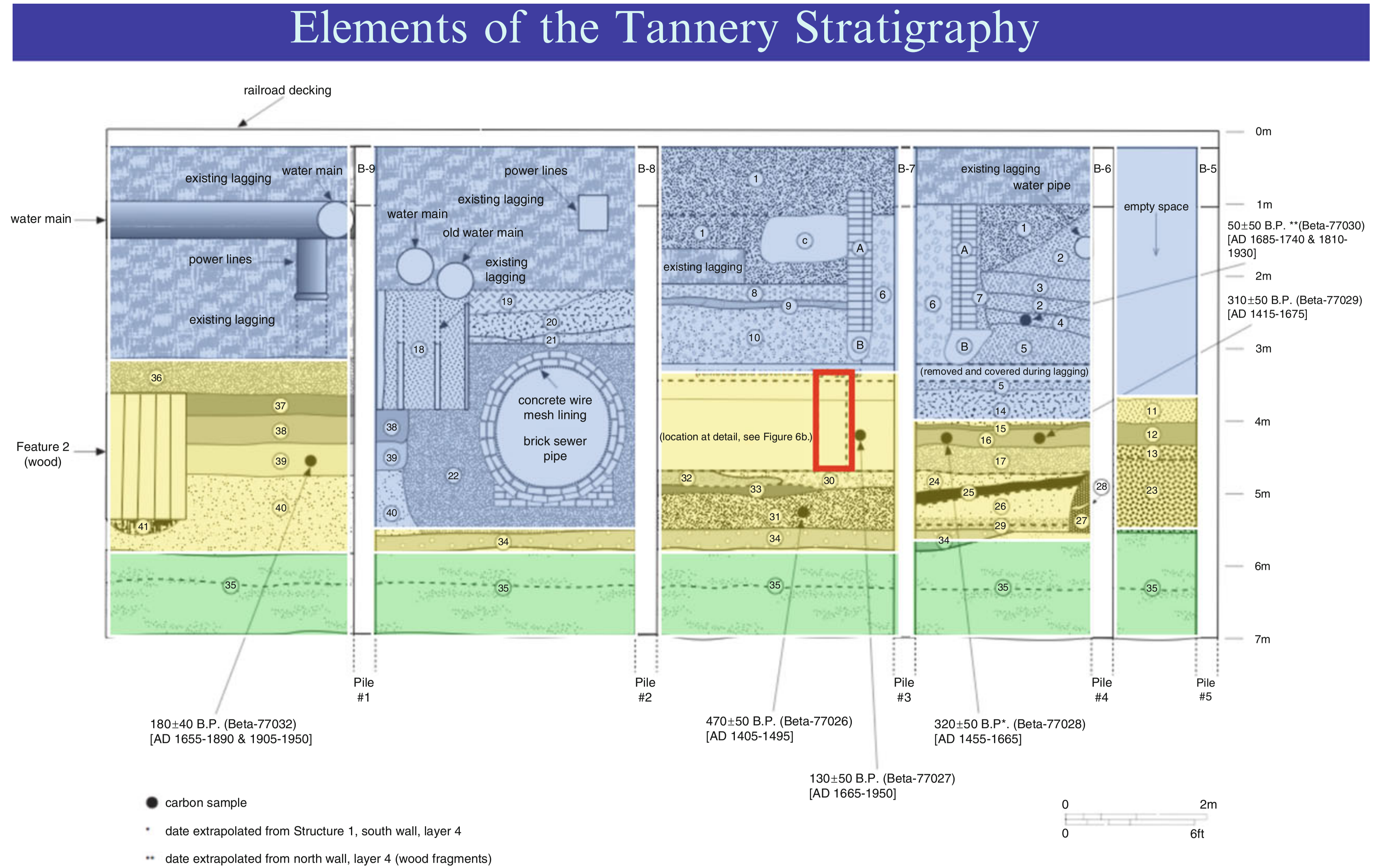
In heavily disrupted urban settings, performance of intensive background research is critical in developing research strategies for any project. The dimensions of a project's footprint become the target of any background research to be performed because the most direct disturbances will occur there and in the immediate vicinity. Since the construction or development will be made atop a previous substrate, recent maps and plans documenting previous building on the location may indicate the existence of earlier design maps and construction plans. These, in turn, could reference buried sediment types, architectural features, utility components, and fill elements that might inform about former site use and landscapes of historic and even prehistoric antiquity.

The density of cultural materials within a confined urban setting often precludes broad, bird's-eye perspectives on site stratigraphy and sedimentation patterns. In such cases, it is important that the geoarchaeologist be familiar with as much background history as possible. Excavations for a subsurface tunnel at the Metropolitan Corrections Center (MCC) in lower Manhattan, New York City, afforded stratigraphic inspections of a complex sequence during evening hours only. Further, such sections were accessible through minimal windows; here, wide exposure could not be provided because of the complex shoring structure needed to maintain on-site stability. A 7 m deep profile exposed a continuous sequence of three stratigraphic sets that facilitated a generic classification of the range of land use succession from later prehistory to the present (Yamin and Schuldenrein, 2007). Each stratigraphic set consisted of sequential depositional bodies that registered a common site formation history. The sets were unconformable (discontinuous) with respect to each other because each successive set marked a turning point in site formation history. Such a classification is useful for the built environment because it introduces a common denominator that helps to isolate patterns of site use and subsequent disturbance.

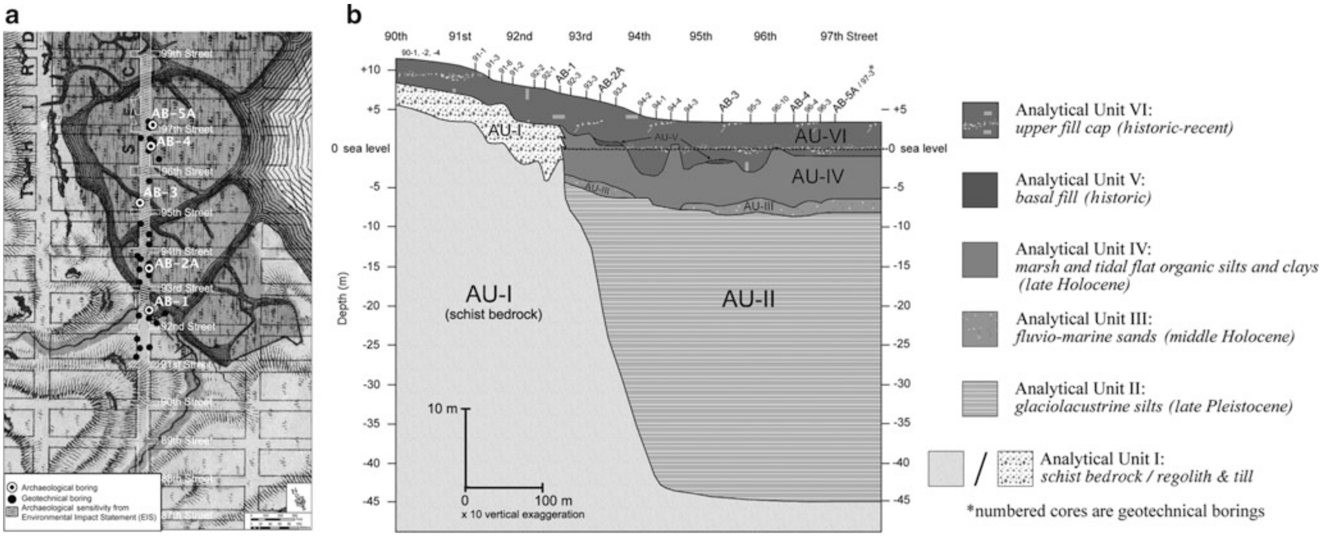
At MCC, the lowermost 1.5 m of sediments was considered a *geogenic set* (Figure 2) and comprised alluvium that was laid down before the first Euroamerican occupations on Manhattan Island. The matrix was largely a homogeneous silty sand capped by a thin, weathered soil (Bw horizon) that marked the uppermost level of the undisturbed river-laid flood material. Radiocarbon dates placed the age of the upper soil at ca. 500 BP. The set is referred to as geogenic because of its geological origins and the absence of any evidence of human impacts within the matrix. Significantly, however, the antiquity of the upper part of this basal profile was equivalent to the time of initial Euroamerican presence in the region.

The overlying 2 m contained evidence for approximately 200 years of historic activity and land use.

Built Environment, Figure 1 Distributions of late Quaternary landform-deposit complexes for geoarchaeological testing along planned sewer line route on the Raritan River, New Jersey. Ages of landforms are per Stone et al. (2002). (**a**) Numbered boxes denote Geoprobe stations selected for coring and analysis. Known archaeological sites are identified. (**b**) Composite stratigraphy of the sequence based on linked soil and sediment sequences. Radiocarbon dates of archaeological age signify tracts of prehistoric site potential. Segment R-9 to R-11 contains the most sensitive deposits.



Built Environment, Figure 2 Detailed stratigraphy of the MCC tunnel sequence, Manhattan, New York City. Three groups of strata are designated: the Built Environment (upper-set3), Historic Levels (middle-set2), and Geogenic components (lower-set1). Component microstrata for each group are based on Harris Matrix criteria. Radiocarbon determinations are presented, and key historic features are specified.



Built Environment, Figure 3 Geoarchaeological sediment stratigraphy for the Second Avenue subway project, Manhattan, New York. (**a**) Field core locations superposed on a historic landform map of the area (Viele, 1874). The tidal drainage net was reconfigured in the eighteenth and nineteenth centuries (From Schuldenrein and Aiuvalasit (2011: Fig. 3)). (**b**) Schematic stratigraphy across the seven-block-long project area. Analytical Units are identified by depositional origin and antiquity (From Schuldenrein and Aiuvalasit (2011: Fig. 9)).

Deposition was characterized by sequential accumulations of more intricate and thinner sediment bodies with primary clasts and finer-grained deposits intermixed with alluvium. The organic component of the matrix was not simply a vegetation mat but also included decayed finds from disaggregated animal parts as well as wood, organic mats, and various debris associated with hide-processing activities; by-products of the former tanneries that surrounded a water impoundment named the Collect Pond by the earliest Dutch settlers of Manhattan. Features of the tanneries were preserved intact – see the barrel identified as Feature 2 (lower left) in Figure 2. Component depositional bodies of this second set were poorly sorted and typically had no cohesive soil or sediment structures. Upon closer inspection and follow-up analyses, microstrata were separable from each other. Their common aspect was that they represented separate stages in a site formation record of eighteenth-century tanning activities, including hide preparation, processing, discard, and resultant sediment disaggregation. This second set preserved the historic levels (Figure 2) and represented the first sustained phases of Euroamerican occupation of the local landscape.

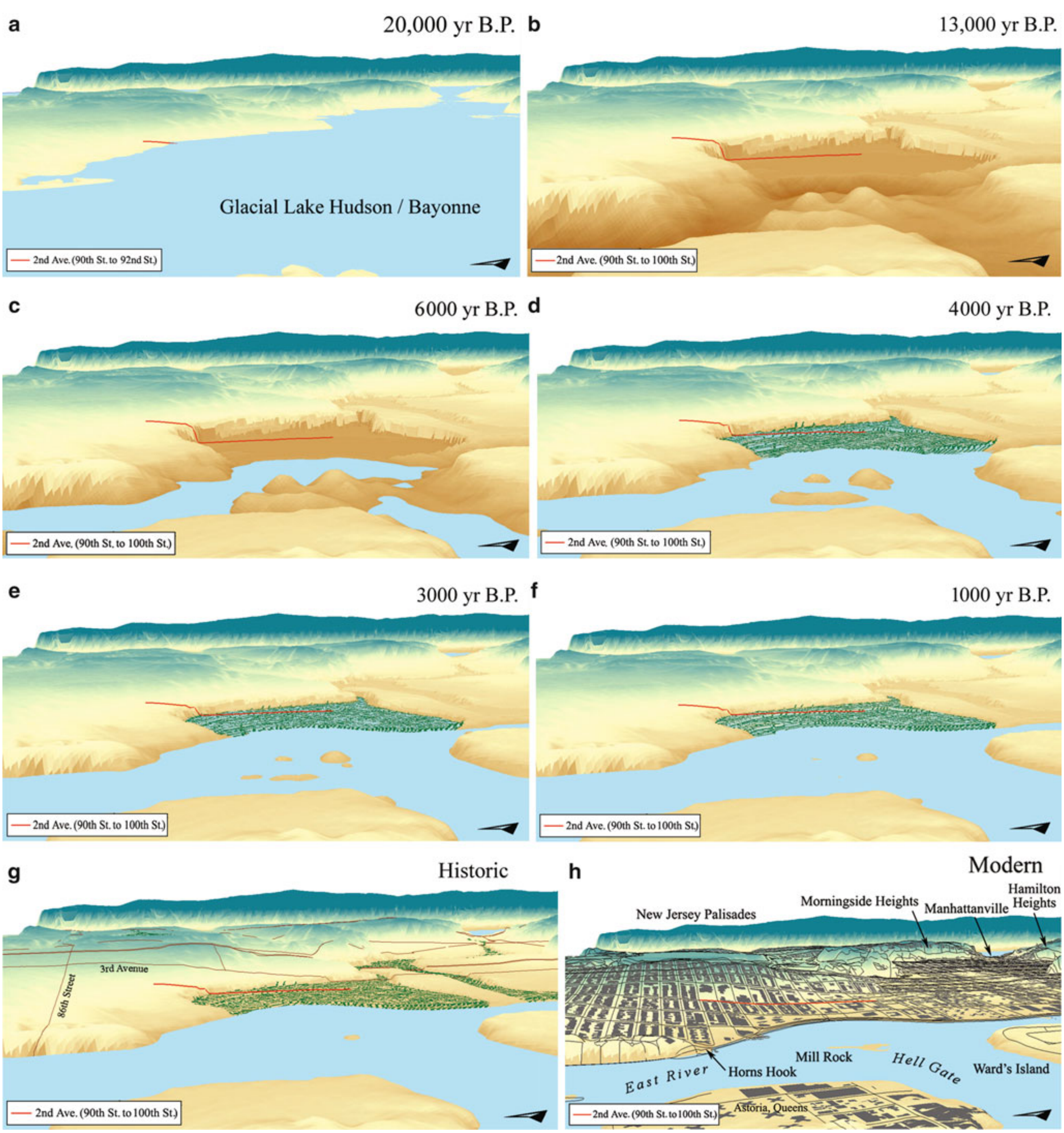
These historic levels were, in turn, overlain by 3 m or more of what would be currently recognized in any vertical exposure as the signature debris of the (late historic to contemporary periods) built environment (Figure 2). The parent matrix was a thick, poorly to nonsorted mass of "fill," very locally offset by pockets of a discrete sediment body. In general, the dominant sands of the parent matrix surround identifiable features of the present environment, specifically structural elements of the subsurface infrastructure (brick-sewer pipe was most prominent, as were water main segments). Within the generic "fill" were pockets of colluvium, debris flow, and even sections of floor that attest to the range of disturbance processes signaling the emergence of the built environment. Isolated archaeological features in this strata set were similar in type to those within the historic levels.

The three sets of strata distill a complex site stratigraphy into the primary phases of site formation history. The Late Holocene stream whose top formed the surface of a stable (probably) prehistoric landform (Set 1) was engineered and modified by the early Dutch and British colonists who utilized it to develop a tanning facility (Set 2). The latter gave way to leveling of the terrain, a sign of the emergence of New York City as a major administrative center in the New World, a position the city holds to this day.

Geoarchaeology of the urban built environment (future strategies)

As the previous example shows, there is an inverse relationship between advancing time and the availability of urban tracts for classic, large-scale, and area-wide archaeological excavations. Advances in remote sensing, GIS mapping, and the application of interdisciplinary methods in sediment analysis (e.g., pollen, microfauna, foraminifera, and malacology) allow geoarchaeologists to expand their interpretive domains as field working opportunities diminish. A major subfield that has emerged is paleoenvironmental reconstruction and, specifically, the ability to develop models of late Quaternary landscape history targeting urban areas. For New World cities, regional

Pleistocene chronologies (in glaciated and nonglaciated areas, shore, riverine, and estuarine environments) were typically unmodified anthropogenically until the Euroamerican arrivals 500 years ago. Colonial accounts coupled with detailed settlement and geological histories present excellent baseline referents for premodification terrain reconstructions. In the Old World, such chronologies are typically of late Holocene antiquity. For example, moderate to large-scale impacts can generally be dated to the Roman period in Europe, while in the Near East, they can extend back to the third millennium BCE. An idealized strategy for exploration in an urban setting is to probe to the contact of the initial natural/cultural-based interface. Very often coring can be applied within such settings, since the



Built Environment, Figure 4 (Continued) probing causes minimal disturbance, and recovery of buried sediments is often substantial enough to characterize the depositional context of the uppermost natural strata.

A major study of this type was performed in 2009 along the footprint of the proposed 2nd Avenue Subway line in New York City's Upper East Side (Schuldenrein and Aiuvalasit, 2011). Here, the density of the underlying utility network was such that a total of only five deep cores could be excavated to terminal Pleistocene levels over a distance of six city blocks (Figure 3a). Preliminary indications of the predisturbance landscape were afforded by historic maps. Moreover, nearly a century ago, an extensive series of nearly 100 borings was conducted in advance of the same subway line, and nearly complete core samples were housed in a storage facility maintained by the NYC Metropolitan Transportation Authority. Examination of these older core specimens allowed researchers to "retrofit" the stratigraphy of the older cores using the newly extracted cores as a stratigraphic baseline. Taken together, the refined 2009 descriptions coupled with the more aerially extensive subsurface mapping of the initial coring effort produced a comprehensive sediment stratigraphy, indexed by radiocarbon dates and broken down by six lithostrata that document the depositional chronology (Figure 3b).

The succession of events begins with the Late Pleistocene lake and upland tills; the subsequent disappearance of the lake and attendant erosion of the till margins; the emergence and sustained evolution of an estuary regulated by marine shoreline cycles during the Middle to Late Holocene; and finally the Euroamerican settlement and rapid modification of the natural shoreline during the industrial and commercial phases of neighborhood development. While the sequence is chronicled by unconsolidated sediments and the radiometric materials that date them, there are temporal gaps of equal or longer duration, attesting to extensive intervals of nondeposition.

Sustained erosion coupled with long-term edaphic adjustments probably account for the absence of early postglacial sediments, while the missing record of the pre-Euroamerican estuary is probably a function of intrusive and large-scale reclamation projects and relandscaping during the historic to recent periods. Additional concerns, for the estuary in particular, include changing sediment budgets (net accretion vs. loss) over the course of a particular geomorphic cycle.

The most detailed chronostratigraphies and reconstructions were developed for estuarine environments that evolved over the interval 4600–3200 BP based on earlier sea-level curves (see Schuldenrein et al., 2007). The significance of that time frame is that it is coincident with the Late Archaic to Woodland transition, which is a key adaptive phase in the regional prehistory of the northeastern coast.

The incorporation of project stratigraphies with regional landform histories permitted the generation of a diachronic model for the evolution of Hell Gate Bay. This is depicted in a time-transgressive, graphic representation of landscape form and process (Figure 4). The "time

Built Environment, Figure 4 GIS-based reconstruction of landscape history in the Second Avenue project area near Hell Gate. A thin line marks the later location of the subway jobsite under construction as of this writing (From Schuldenrein and Aiuvalasit (2011: Fig. 11)). (**a**) Pleistocene glacial Lake Hudson-Bayonne complex inundates most of the project area. Lake elevations are ~30 ft (9 m) higher than modern sea level. The terrain above 92nd street was submerged; the segment between 90th and 92nd streets was not. This is consistent with field results because lacustrine sediments were not identified between 90th and 92nd streets but were prominent in all cores to the north. (**b**) Drainage of the glacial lakes and incision of lacustrine deposits. By 13,000 year BP, the proglacial lakes had drained, and sea level was 22 m below modern levels. Exposed, steep-sided terraces flanked the ancestral trenches of the Harlem and East Rivers. The project area was perched above the floodplain. It is probable that small tributaries from Manhattan drained across the project area, although no evidence for these was observed in the cores. (**c**) Emerging nearshore environment. By 6000 year BP, sea level had risen to −11 m, and marine waters encroached onto the proximal edges of the lake terrace. During this very dynamic time, a complex of freshwater fluvial sands and transgressing marine deposits began aggrading atop the lacustrine terrace surface. (**d**) Estuarine formation. At 4000 year BP, the entire terrace surface was subject to tidal cycles, as sea level had risen to between −6 and −7 m. Organic muck and silts suggest the formation of marshes, which would have transgressed across the project area commensurate with rising sea level. The presence of freshwater pollen species indicates that, at these early stages of estuarine formation, the marsh still had a significant freshwater component. This would have been a habitat optimally suited for prehistoric (Late Archaic) activity, with convenient access to marine and terrestrial resources. (**e**) Zoned salt flats. Landward advance of mesohaline marshes (proximal) and subaqueous saline mud flats (distal). By 3000 year BP, fringing marsh biomes continued to develop, and the majority of the project terrain consisted of subaqueous mud flats. From 4000 to 3000 year BP, estuarine sedimentation is registered by mineral and organic sediment, reflecting pulses in sea-level rise. Shortly after 3000 year BP, the mud flats had stopped aggrading in response to general deceleration of sea-level rise. The environment would have remained attractive to later prehistoric groups (transitional Archaic to Woodland). (**f**) Stabilized subaqueous saline mud flat. At 1000 year BP, the landscapes reached a homeostatic state. This is signaled by the minimal accumulations of organic material on the mud flat bottoms. (**g**) Historic saline, thinly vegetated mud flat. The landform is referred to historically as a "meadowlands." During the early Euroamerican period, surfaces were level, subject only to tidal cycles. Thin and diffuse organic lenses and minor peats implicate changing (humanly influenced) edaphic conditions as subaqueous vegetation communities expanded across the landform. (**h**) Modern land surface built up by domestic debris, construction material, and fill. The infilling during the late nineteenth century reclaimed the major land segments of Hell Gate Bay. The landform was capped with ~3–6 m of fill material to raise shore elevations 4–4.5 m above sea level.

slices" were created using a combination of modern elevation data, historical bathymetry, historical landform maps, and projected sea-level information. A digital elevation model (DEM) for the Central Park Quadrangle (USGS 7.5 min series topographic maps) was used as the base, and it was modified within a Geographic Information System (GIS) to reflect the pre-landfill topography of parts of the Harlem plain. Bathymetry was digitized from a georeferenced digital image of the "Navigation Chart of Hell Gate and its approaches" (Survey of the Coast of the United States, 1851) retrieved from the image archives of the Historical Map and Chart Collection of the Office of Coast Survey, National Ocean Service, NOAA. This chart was considered more accurate than modern bathymetric data, as it predates most of the late nineteenth- and early twentieth-century dredging activities. The location and outline of the historic period's low-lying wetlands was digitized from a georeferenced image of the map "Sanitary & Topographical Map of the City and Island of New York" (Viele, 1874). The elevation of this wetland was lowered for older time periods in accordance with information generated in the course of this study's subsurface investigations.

This model generated eight temporal projections for landform evolution (Figure 4a–h). The temporal projections correspond to key occupation periods in the northeastern prehistoric chronology and afford a glimpse at the subsistence environments utilized during these time frames.

More challenging geoarchaeological issues await as the reach of historic site formation studies extends into the analyses of anthropogenic sediments. Accordingly, the multiple transformations of sediments and soils are just now being explored by specialists utilizing x-ray diffraction and florescence methods as well as elemental chemical assays using inductively coupled plasma-mass spectrometry (ICP-MS). While these approaches have been successfully applied to reconstructing land use practices in early complex settlements (i.e., Near Eastern tells, late prehistoric North American villages), the multiplicity of post-abandonment factors modifying historic sediments and artifact clusters are only now being explored – see Holliday (2004) and Howard et al. (2015).

Summary

The geoarchaeology of the built environment represents a new platform for research. Its development is intimately connected with the emerging template of a new geological epoch, the Anthropocene. Geoarchaeological work can and must be coupled with a changing archaeological practice, one that views opportunity through the prism of sustainability and research designs that are fashioned by the new imposed research universe. The archaeology of the built environment is guided by an almost "minimalist" approach wherein high data yield through science and technology is rapidly replacing labor-intensive strategies in large and expansive dig sites. Geoarchaeology will be undertaken across landscapes that are increasingly affected by human impacts. Since funding and opportunity will be generated by development interests, the methods and strategies applied by geoarchaeologists will be increasingly oriented toward urban environments where stratigraphies are complex and predominantly cultural. Within the built environment, natural processes of sedimentation will likely become less significant. These changing archaeological landscapes provide new and uncharted opportunities for geoarchaeologists to practice their craft.

Bibliography

Brown, A. G., Basell, L. S., and Butzer, K. W. (eds.), 2011. *Geoarchaeology, Climate Change, and Sustainability*. Boulder, CO: Geological Society of America. GSA Special Paper, Vol. 476.

Butzer, K. W., 1964. *Environment and Archaeology: An Introduction to Pleistocene Geography*. Chicago: Aldine.

Carver, J., 2013. The challenges and opportunities for mega-infrastructure projects and archaeology. *Papers from the Institute of Archaeology*, **23**(1), article 18. http://www.pia-journal.co.uk/articles/10.5334/pia.437/

Crossrail Project, http://www.crossrail.co.uk/sustainability/archaeology/

Egidi, R., Filippi, F., and Martone, S. (eds.), 2010. *Archeologia e infrastrutture: il tracciato fondamentale della linea C della metropolitana di Roma: prime indagini archeologiche*. Firenze: L. S. Olschki.

Fischer-Kowalski, M., Krausmann, F., and Pallua, I., 2014. A sociometabolic reading of the Anthropocene: modes of subsistence, population size and human impact on Earth. *The Anthropocene Review*, **1**(1), 8–33.

Harris, E. C., 1989. *Principles of Archaeological Stratigraphy*. London: Academic.

Hattam, J., 2015. Underground transit projects reveal secrets buried beneath cities. *Discover Magazine*, July 23, 2015, http://discovermagazine.com/2015/sept/13-city-layers

Holliday, V. T., 2004. *Soils in Archaeological Research*. New York: Oxford University Press.

Howard, J. L., Ryzewski, K., Dubay, B. R., and Killion, T. W., 2015. Artifact preservation and post-depositional site formation processes in an urban setting: a geoarchaeological study of a 19th century neighborhood, in Detroit, Michigan USA. *Journal of Archaeological Science*, **53**, 178–189.

Istanbul Arkeoloji Müzeleri, 2012. *Stories from the Hidden Harbor: Shipwrecks of Yenikapı*. Istanbul: Istanbul Archaeological Museums Press.

Lewis, A.-E. H. (ed.), 2001. *Highway to the Past: The Archaeology of Boston's Big Dig*. Boston: William Francis Galvin, Secretary of the Commonwealth, Chairman, Massachusetts Historical Commission.

Lewis, S. L., and Maslin, M. A., 2015. Defining the Anthropocene. *Nature*, **519**(7542), 171–180.

Nevle, R. J., and Bird, D. K., 2008. Effects of syn-pandemic fire reduction and reforestation in the tropical Americas on atmospheric CO_2 during European conquest. *Palaeogeography Palaeoclimatology Palaeoecology*, **264**(1–2), 25–38.

NHPA (National Historic Preservation Act, 1966 (as amended in 2006). 16 U.S.C. 470. Advisory Council on Historic Preservation, electronic document: http://www.achp.gov/nhpa.html (accessed December 2015).

Perinçek, D., 2010. The geoarchaeology of the Yenikapı excavation site in the last 8000 years and geological traces of natural

disasters (İstanbul – Turkey). *Mineral Research and Exploration Bulletin (Ankara)*, **141**, 69–92.
Pulak, C., Ingram, R., and Jones, M., 2015. Eight Byzantine shipwrecks from the Theodosian harbour excavations at Yenikapı in Istanbul, Turkey: an introduction. *International Journal of Nautical Archaeology*, **44**(1), 39–73.
Rapoport, A., 1990. *The Meaning of the Built Environment: A Nonverbal Communication Approach*, 2nd edn. Tucson: University of Arizona Press.
Rodning, C., 2010. Place, landscape, and environment: anthropological archaeology in 2009. *American Anthropologist*, **112**(2), 180–190.
Rothschild, N. A., and diZerega Wall, D., 2014. *The Archaeology of American Cities*. Gainesville: University Press of Florida.
Ruddiman, W. F., 2013. The Anthropocene. *Annual Review of Earth and Planetary Sciences*, **41**, 45–68.
Schuldenrein, J., 2006. Emergence of geoarchaeology in research and cultural resource management: Part I. *The SAA Archaeological Record*, **6**(5), 11–14.
Schuldenrein, J., and Aiuvalasit, M., 2011. Urban geoarchaeology and sustainability: a case study from Manhattan Island, New York City, USA. In Brown, A. G., Basell, L. S., and Butzer, K. W. (eds.), *Geoarchaeology, Climate Change, and Sustainability*. Boulder, CO: Geological Society of America. GSA Special Paper, Vol. 476, pp. 153–172.
Schuldenrein, J., Larsen, C. E., Aiuvalasit, M. A., Smith, M. A., and Malin-Boyce, S., 2007. *Geomorphological/Archaeological Borings and GIS Model of the Submerged Paleoenvironment in the New York/New Jersey Harbor and Bight in Connection with the New York and New Jersey Harbor Navigation Project, Port of New York and New Jersey*. Portland, Maine: Report prepared for NEA, Inc.
Seasholes, N. S., 2003. *Gaining Ground: A History of Landmaking in Boston*. Cambridge, MA: MIT Press.
Stone, B. D., Stanford, S. D., and Witte, R. W., 2002. Surficial geological map of northern New Jersey. U.S. Geological Survey Miscellaneous Investigations Map I-2540. Trenton, NJ, scale 1:100,000.
Survey of the Coast of the United States, 1851. Hell Gate and its approaches, scale 1:5,000.
Viele, E. L., 1874. Topographical atlas of the City of New York including the annexed territory, showing original water courses and made land. Prepared under the direction of Egbert L. Viele, civil and topographical engineer. New York: Map Division, New York Public Library, scale 1:12,000.
Waters, C. N., Zalasiewicz, J. A., Williams, M., Ellis, M. A., and Snelling, A. M., 2014. A stratigraphical basis for the Anthropocene? In Waters, C. N., Zalasiewicz, J. A., Williams, M., Ellis, M. A., and Snelling, A. M. (eds.), *A Stratigraphical Basis for the Anthropocene*. London: The Geological Society, pp. 1–21. Geological Society, London, Special Publication 395(1).
Yamin, R., and Schuldenrein, J., 2007. Landscape archaeology in lower Manhattan: the collect pond as an evolving cultural landmark in early New York City. In Hicks, D., McAtackney, L., and Fairclough, G. J. (eds.), *Envisioning Landscape: Situations and Standpoints in Archaeology and Heritage*. Walnut Creek, CA: Left Coast Press, pp. 75–100.

Cross-References

Dumps and Landfill
Geographical Information Systems (GIS)
Harris Matrices and the Stratigraphic Record
Paleoenvironmental Reconstruction
Soils

BURNED-ROCK FEATURES

Alston V. Thoms
Department of Anthropology, Texas A&M University, College Station, TX, USA

Synonyms

Burnt-rock features; Fire-altered rock features; Fire-cracked rock features; Fire-modified rock features; Heat-retainer features; Thermally altered rock features

Definitions

Burned rock. Rock, commonly limestone, sandstone, quartzite, basalt, granodiorite, and metamorphic mudstone, that was purposefully heated to 500 °C or higher, resulting in discoloration, cracking, and fragmentation.

Burned-rock features. In situ concentrations of burned rocks representing the heating elements of thermal facilities as well as exhausted/discarded parts thereof. These features were most commonly used for baking, steaming, stone-boiling, and grilling food; also for hot-water and steam bathing; as flooring in metal-making furnaces, ceramic and charcoal kilns; and for other manufacturing purposes.

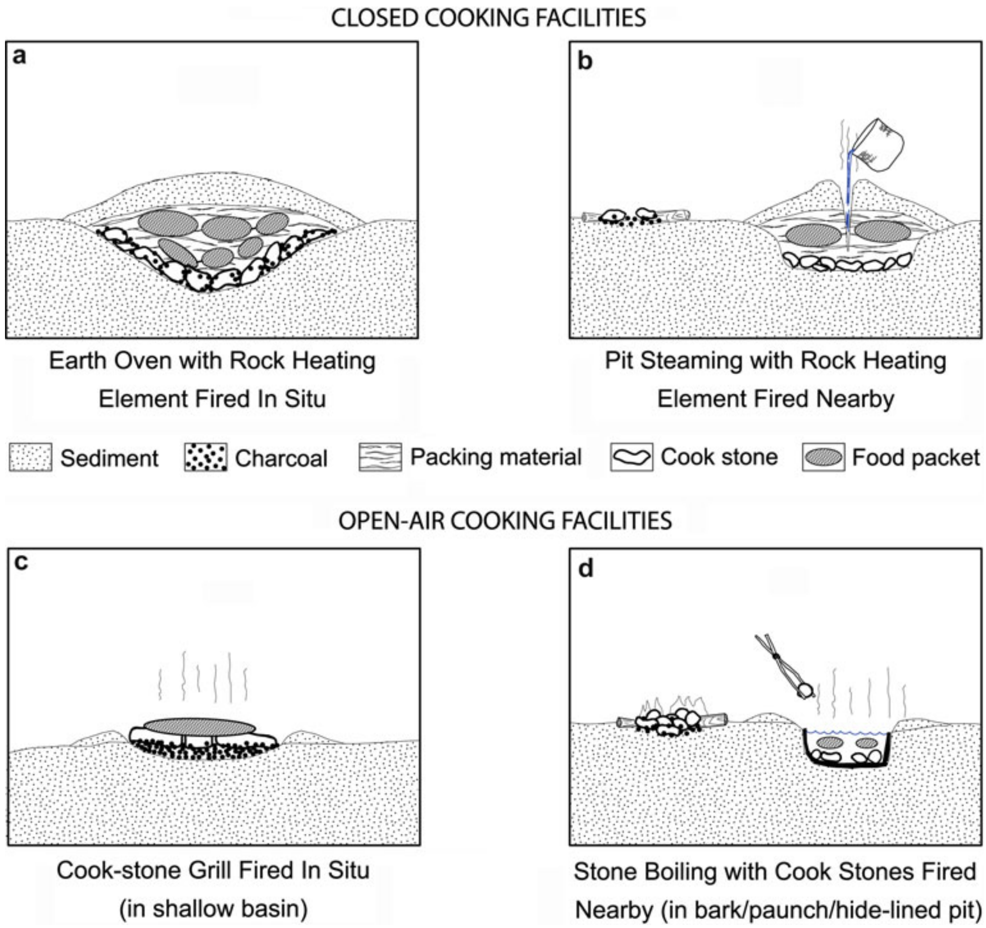
Cook-stone technology. Processes employed in the procurement, utilization, and discard of rocks that served as heating elements for cooking food; in regions where suitable rocks did not occur naturally, people often manufactured cooking stones by shaping and firing clay nodules.

Introduction

Burned-rock features are known worldwide from historical, ethnographic, and archaeological records. This entry focuses on cooking-related, burned-rock features, which account for the most common and ancient usage of heated stones from as early as ca. 32,000 years BP. Such stones are widely known archaeologically as fire-cracked rock (FCR). As products and byproducts of human activity, FCR from cooking features is among the most ubiquitous of artifacts. In behavioral realms, FCR served primarily as heating elements – cook-stones – in surface hearths, earth ovens, steaming pits, and for boiling. Composed mainly of cobble-size rocks (6.4–25.6 cm in maximum dimension), cook-stone features are structurally resistant to natural, soil/sediment-disturbance processes, and hence, they have considerable research value.

Research contexts and status

The human digestive tract requires consistent intake of cooked foods (Wrangham, 2009). Compared to short-term cooking over direct flames and on/in hot coals, prolonged baking and stone boiling render many foods more calorie-rich. Worldwide similarities in hot-rock cooking techniques and features result from the fact that plant and animal tissues with comparable biochemical properties



Burned-Rock Features, Figure 1 Four generic cook-stone feature types found in western North America: (**a**) earth oven; (**b**) steaming pit; (**c**) surface griddle; (**d**) stone boiling.

respond similarly to the application of heat and moisture (Wandsnider, 1997). The advent and proliferation of earth-oven and stone-boiling techniques have been identified as indicators of dietary changes and human evolution, notably smaller teeth, via increased consumption of fat, well-cooked meat, and complex carbohydrates (e.g., Brace, 2005; Thoms, 2008a). Integration of hot-rock cooking into subsistence strategies affords fuel-sparing and heat-conserving benefits that facilitate utilizing a greater proportion of a given region's food-resource potential (Thoms, 2009).

In North America (especially the south-central region), Europe, and Australia, cook-stone technology research is well developed, and it is increasingly underway elsewhere around the world (Driver and Massey, 1957; Doleman, 1996; Petraglia, 2002). Burned-rock features, nonetheless, remain under-studied. They lack a unifying nomenclature equivalent to lithic and ceramic technologies or soil-formation processes. Widely available syntheses tend be geographically limited, temporally restricted, or focused on specific hot-rock cooking techniques (e.g., Wandsnider, 1997; Odgaard, 2003; Straus, 2006; Thoms, 2008b; Nelson, 2010). Much of the relevant research remains obscure, presented in proceedings volumes (e.g., Buckley, 1990; Hodder and Barfield, 1991; Frère-Sautot, 2003), cultural resource management monographs (e.g., Schalk and Meatte, 1993; Black et al., 1997; Mehalchick et al., 2004), dissertations (e.g., Wolynec, 1977; Thoms, 1989; Soler Mayor 1996; Peacock, 1998; Stark, 2002; Yu, 2006; Lucquin, 2007; Graf, 2008), and theses (e.g., Jackson 1998; Clabaugh, 2002; Acuña, 2006).

Functional and morphological variation

Figure 1 illustrates four generic types of hot-rock cookery from western North America that are also common around the world. Each exhibits considerable variation in construction, size, morphology, and rock type(s), as demonstrated by varied descriptions of earth ovens and stone-boiling features (e.g., Thoms, 1989; Black et al., 1997; Wandsnider, 1997; Stark, 2002; Nelson, 2010). Figure 2 illustrates examples of cook-stone features from sites in western North America that are also exemplary of those

Burned-Rock Features, Figure 2 Examples of cook-stone features at archaeological sites in western North America: (**a**) small surface griddle in south-central Texas; (**b**) small earth oven exposed along a reservoir shoreline in east-central Texas; (**c**) plan view of a large earth oven in northeastern Washington; (**d**) cross section of another large earth oven at the same site in northeastern Washington; (**e**) cross section of burned-rock mound with embedded large earth ovens in central Texas; and (**f**) base of a large, slab-lined earth oven in the same mound at the same site in central Texas (various scales; author's photographs).

found in many other regions. Open-air/griddle hearths, earth ovens, steaming pits, and stone-boiling features 40–100 cm in diameter are suitable for family-size groups within or outside residential structures. Larger features, for example, earth ovens with heating elements 2–3 m in horizontal extent, are indicative of outdoor cooking exclusively. Most FCR mounds (ca. 6–15 m × 0.75–1.5 m) are accumulations – spanning decades, centuries, and, occasionally several millennia – of spent rocks from large ovens or from small cooking facilities at a nearby residential site.

Non-cooking activities also yield FCR. Ethnographic accounts of steam bathing in hot-rock saunas are common, but resulting features are underrepresented archaeologically (Barfield and Hodder, 1987). A few burned-rock mounds in Ireland and the United Kingdom are interpreted as the remains of hot-water or steam-bathing facilities. Other burned-rock features in Europe, and likely elsewhere, served as flooring in ceramic and charcoal kilns, metal-making furnaces, and for other manufacturing purposes (Buckley, 1990; Hodder and Barfield, 1991; Frère-Sautot, 2003).

Analytical methods

Ground-penetrating radar, magnetometry, and other remote sensing techniques are used to locate buried burned-rock features (e.g., Mehalchick et al., 2004). Geoarchaeological studies afford reliable measures of their structural integrity (e.g., Leigh 2001; Thoms, 2007). Paleomagnetic analysis can distinguish between rocks heated and cooled in place, as would be expected of earth ovens and griddles, and those heated in one place and cooled in another, as in stone boiling (Gose, 2000). Actualistic and laboratory cooking experiments suggest that rocks exhibit distinctive fracture patterns and other thermal weathering characteristics depending on whether they cooled slowly, as in earth ovens, or rapidly, as in stone boiling (e. g., House and Smith, 1975; McParland, 1977; Schalk and Meatte, 1993; Jackson, 1998). With varying degrees of success, gas chromatography, fatty acid, Fourier transform infrared spectroscopy (FTIR), and plant-microfossil analyses have been applied to FCR to determine what foods they cooked (e.g., Quigg et al., 2001; Buonasera, 2005; Lucquin, 2007; Cummings et al., 2011; Laurence et al., 2011; Malainey, 2011; Perry and Quigg, 2011). Luminescence dating has been done on FCR and fired clay nodules from earth ovens (Roberts, 1997). Distributions and ages of burned-rock features figure prominently in establishing geomorphic histories of landscapes (e.g., Mandel, 2000; Fanning et al., 2008).

Age and global distribution

Hot-rock cookery and, hence, formation of burned-rock features was underway 35,000–31,000 years ago in Europe (Movius, 1966; Straus, 2006), Japan (Dogome, 2000), Australia (Gillespie, 1997), and the Bismarck Archipelago (Torrence et al., 2004). It was evident by the terminal Pleistocene or early Holocene in Africa (e.g., Zerboni, 2011), the Middle East (McCorriston et al., 2002), India (e.g., Nambi and Murty, 1983), China (e.g., Madsen et al., 2006), Siberia (e.g., Graf, 2008), and North America (Homsey, 2009; Thoms, 2009). In Greenland, slab-lined, rock-filled heaths (i.e., box-hearths) were common in paleo-Eskimo houses by 4500–3900 BP (Odgaard, 2003). Earth ovens were in use by 6000 BP in South America (Stahl and Oyuela-Caycedo, 2007; Iriarte et al., 2008; van den Bel, 2010) and in Polynesian by 1000 BP (e.g., Carson, 2002). Most of the world's regions witnessed increases in diversity, density, and size of burned-rock features during the Holocene (e.g., Stark, 2002; Thoms, 2009).

Summary

Burned-rock features are known worldwide; most commonly they represent the remains of thermal facilities and exhausted/discarded parts of such installations that were used in baking, steaming, stone-boiling, and grilling food. Integration of cook-stone technology into land-use strategies, beginning ca. 32,000 BP, afforded an important means of utilizing a greater proportion of a given region's food resource potential and thereby contributed significantly to the long-term maintenance of our species. The information potential of cook-stone features, however, remains surprisingly under-studied, given that they are ubiquitous, often well preserved, and span tens of millennia of the human experience.

Bibliography

Acuña, L. I., 2006. *The Economic Contribution of Root Foods and Other Geophytes in Prehistoric Texas*. Unpublished Master's Thesis, San Marcos, Department of Anthropology, Texas State University.

Barfield, L. H., and Hodder, M. A., 1987. Burnt mounds as saunas and the prehistory of bathing. *Antiquity*, **61**(233), 370–379.

Black, S. L., Ellis, L. W., Creel, D. G., and Goode, G. T., 1997. *Hot Rock Cooking on the Greater Edwards Plateau: Four Burned Rock Midden Sites in West Central Texas*. Austin: Texas Archeological Research Laboratory, The University of Texas. Studies in Archeology, Vol. 22.

Brace, C. L., 2005. "Neutral theory" and the dynamics of the evolution of "modern" human morphology. *Human Evolution*, **20**(1), 19–38.

Buckley, V. M. (ed.), 1990. *Burnt Offerings: International Contributions to Burnt Mound Archaeology*. Dublin: Wordwell.

Buonasera, T., 2005. Fatty acid analysis of prehistoric burned rocks: a case study from central California. *Journal of Archaeological Science*, **32**(6), 957–965.

Carson, M. T., 2002. Ti ovens in polynesia: ethnographic and archaeological perspectives. *Journal of the Polynesian Society*, **111**(4), 270–339.

Clabaugh, P. A., 2002. *Preserving the Feature Record: A Systematic Analysis of Cooking and Heating Features from the Richard Beene Site (41BX831), Texas*. Unpublished Master's Thesis, College Station, Department of Anthropology, Texas A&M University.

Cummings, L. S., Puseman, K., Logan, M. K., and Varney, R. A., 2011. Pollen, macrofloral, organic residue (FTIR) analysis, charcoal identification, and AMS radiocarbon dating of samples from Sites 45SN28 and 45SN303, Washington. In Chatters, J. C., LeTourneau, P. D., and Rooke, L. C. (eds.), *Understanding Olcott: Data Recovery at 45SN28 and 45SN303, Snohomish County, Washington*. Bothell: AMEC Erath & Environmental. Appendix F (not paginated), vol. 2. Granite Falls Alternate Route Project, Department of Public Works, Snohomish County, Washington.

Dogome, H., 2000. Summary [in English]. In Sakaguchi, K., and Dogome, H. (eds.), *Yokomine C Site [in Japanese]*. Kagoshima: Minamitane-cho Board of Education, pp. 1–2.

Doleman, W. (compiler), 1996. FCR (Fire-Cracked Rock) Bibliography. Tennessee Archaeology Net Bibliography Page: http://www.mtsu.ed/~kesmith/TNARCHNET/Pubs/fcr.html. Accessed 20 Dec 2011.

Driver, H. E., and Massey, W. C., 1957. *Comparative Studies of North American Indians, part 2*. Philadelphia: American Philosophical Society. Transactions of the American Philosophical Society, New Series, Vol. 47.

Fanning, P. C., Holdaway, S. J., and Rhodes, E. J., 2008. A new geoarchaeology of aboriginal artefact deposits in western NSW, Australia: establishing spatial and temporal geomorphic controls on the surface archaeological record. *Geomorphology*, **101**(3), 524–532.

Frère-Sautot, M.-C. (ed.), 2003. *Le feu domestique et ses structures au néolithique et aux âges des métaux [Domestic Fire and its Structures from the Neolithic and the Metal Ages]*. Montagnac: Editions Monique Mergoil. Prehistories, Vol. 9.

Gillespie, R., 1997. Burnt and unburnt carbon: dating charcoal and burnt bone from the Willandra Lakes, Australia. *Radiocarbon*, **39**(3), 239–250.

Gose, W. A., 2000. Palaeomagnetic studies of burned rocks. *Journal of Archaeological Science*, **27**(5), 409–421.

Graf, K. E., 2008. *Uncharted Territory: Late Pleistocene Hunter-Gatherer Dispersals in the Siberian Mammoth-Steepe*. Unpublished PhD Dissertation, Reno, Department of Anthropology, University of Nevada.

Hodder, M. A., and Barfield, L. H. (eds.), 1991. *Burnt Mounds and Hot Stone Technology.* West Bromwich: Sandwell Metropolitan Borough Council.

Homsey, L. K., 2009. The identification and prehistoric selection criteria for fire-cracked rock: an example from Dust Cave, Alabama. *Southeastern Archaeology*, **28**(1), 101–116.

House, J. H., and Smith, J. W., 1975. Experiments in the replication of fire-cracked rock. In Shiffer, M. B., and House, J. H. (eds.), *The Cache River Archaeological Project*. Fayetteville: Arkansas Archaeological Survey. Research Series, Vol. 8, pp. 75–80.

Iriarte, J., Gillam, C. J., and Marozzi, O., 2008. Monumental burials and memorial feasting: an example from the southern Brazilian Highlands. *Antiquity*, **82**(318), 947–961.

Jackson, M. A., 1998. *The Nature of Fire-Cracked Rock: New Insights from Ethnoarchaeological and Laboratory Experiments*. Unpublished MA Thesis, College Station, Department of Anthropology, Texas A&M University.

Laurence, A. R., Thoms, A. V., Bryant, V. M., and McDonough, C., 2011. Airbone starch granules as a potential contamination source at archaeological sites. *Journal of Ethnobiology*, **31**(2), 213–232.

Leigh, D. S., 2001. Buried artifacts in sandy soils: techniques for evaluating pedoturbation versus sedimentation. In Goldberg, P., Holliday, V. T., and Ferring, C. R. (eds.), *Earth Sciences and Archaeology.* New York: Kluwer/Plenum, pp. 269–293.

Lucquin, A., 2007. *Etude physico-chimique des méthodes de cuisson pré et protohistorique [Physico-Chemical Study of Pre- and Protohistoric Cooking Methods]*. Unpublished PhD Dissertation, Rennes, France, Department of Archaeology and Archaeo-Sciences, University of Rennes.

Madsen, D. B., Haizhou, M., Brantingham, J. P., Xing, G., Rhode, D., Haiying, Z., and Olsen, J. W., 2006. The late Upper Paleolithic occupation of the northern Tibetan Plateau margin. *Journal of Archaeological Science*, **33**(10), 1433–1444.

Malainey, M. E., 2011. *A Consumer's Guide to Archaeological Science: Analytical Techniques*. New York: Springer.

Mandel, R. D. (ed.), 2000. *Geoarchaeology in the Great Plains*. Norman: University of Oklahoma Press.

McCorriston, J., Oches, E. A., Walter, D. E., and Cole, K. L., 2002. Holocene paleoecology and prehistory in highland Southern Arabia. *Paléorient*, **28**(1), 61–88.

McParland, P., 1977. Experiments in firing and breaking rocks. *Calgary Archaeologist*, **5**, 31–33.

Mehalchick, G., Boyd, D. K., Kibler, K. W., and Ringstaff, C. W. (eds.), 2004. *Shifting Sands and Geophytes: Geoarchaeological Investigations at Paluxy Sites on Fort Hood*. Fort Hood: United States Army Fort Hood. Archeological Resource Management, Vol. 48.

Movius, H. L., Jr., 1966. The hearths of the Upper Périgordian and Aurignacian horizons at the Abri Pataud, Les Eyzies (Dordogne) and their possible significance. Recent Studies in Paleoanthropology, no. 2, part 2. *American Anthropologist*, **68**(2), 296–325.

Nambi, K. S. V., and Murty, M. L. K., 1983. An Upper Paleolithic fireplace in Kurnool Caves, South India. *Bulletin of the Deccan College Post-Graduate and Research Institute*, **42**, 110–118.

Nelson, K., 2010. Environment, cooking strategies and containers. *Journal of Anthropological Archaeology*, **29**(2), 238–247.

Odgaard, U., 2003. Hearth and home of the Palaeo-Eskimos. *Études/Inuit/Studies*, **27**(1–2), 349–374.

Peacock, S. L., 1998. *Putting Down Roots: The Emergence of Wild Plant Food Production on the Canadian Plateau*. Unpublished Ph.D. Dissertation, Victoria, British Columbia, School of Environmental Studies, University of Victoria.

Perry, L., and Quigg, J. M., 2011. Starch remains and stone boiling in the Texas Panhandle, part I: the pipeline, Corral, and Pavilion Sites. *Plains Anthropologist*, **56**(218), 95–107.

Petraglia, M. D., 2002. The heated and the broken: thermally altered stone, human behavior, and archaeological site formation. *North American Archaeologist*, **23**(3), 241–269.

Quigg, J. M., Malainey, M. E., Przybylski, R., and Monks, G., 2001. No bones about it: using lipid analysis of burned rock and groundstone residue to examine Late Archaic subsistence practices in South Texas. *Plains Anthropologist*, **46**(177), 283–303.

Roberts, R. G., 1997. Luminescence dating in archaeology: from origins to optical. *Radiation Measurements*, **27**(5–6), 819–892.

Schalk, R., and Meatte, D., 1993. The archaeological features. In Samules, S. R. (ed.), *The Archaeology of Chester Morse Lake: Long-Term Human Utilization of the Foothills in the Washington Cascade Range*. Pullman: Center for Northwest Anthropology, Washington State University, pp. 10.3–10.42.

Soler Mayor, B., 1996. *Propuesta de normalización en el reconocimiento y diagnosis de las termoalteraciones de las rocas carbonatadas en contexto arqueológico* [Standardization Proposal on the Recognition and Diagnosis of the Thermal Alteration of Carbonaceous Rocks in Archaeological Context]. Unpublished PhD Dissertation, Valencia, Spain, Department of Prehistory and Archaeology, University of Valencia.

Stahl, P. W., and Oyuela-Caycedo, A., 2007. Early prehistoric sedentism and seasonal animal exploitation in the Caribbean lowlands of Colombia. *Journal of Anthropological Archaeology*, **26**(3), 329–349.

Stark, R. T., 2002. *Comidas de la Tierra: An Ethnoarchaeology of Earth Ovens*. Unpublished PhD Dissertation, Austin, Department of Anthropology, The University of Texas.

Straus, L. G., 2006. Of stones and bones: interpreting site function in the Upper Paleolithic and Mesolithic of western Europe. *Journal of Anthropological Archaeology*, **25**(4), 500–509.

Thoms, A. V., 1989. *The Northern Roots of Hunter-Gatherer Intensification: Camas and the Pacific Northwest*. Unpublished PhD Dissertation, Pullman, Department of Anthropology, Washington State University.

Thoms, A. V., 2007. Fire-cracked rock features on sandy landforms in the Northern Rocky Mountains: toward establishing reliable frames of reference for assessing site integrity. *Geoarchaeology*, **22**(5), 477–510.

Thoms, A. V., 2008a. Ancient Savannah roots of the carbohydrate revolution in South-Central North America. *Plains Anthropologist*, **53**, 121–136.

Thoms, A. V., 2008b. The fire stones carry: ethnographic records and archaeological expectations for hot-rock cookery in western North America. *Journal of Anthropological Archaeology*, **27**(4), 443–460.

Thoms, A. V., 2009. Rocks of ages: propagation of hot-rock cookery in western North America. *Journal of Archaeological Science*, **36**(3), 573–591.

Torrence, R., Neall, V., Doelman, T., Rhodes, E., McKee, C., Davies, H., Bonetti, R., Gugliemetti, A., Manzoni, A., Oddone, M., Parr, J., and Wallace, C., 2004. Pleistocene colonisation of the Bismarck Archipelago: new evidence from West New Britain. *Archaeology in Oceania*, **39**(3), 101–130.
van den Bel, M., 2010. A description of Late Archaic rock-filled pits in French Guiana. *Revista de Arqueologia*, **23**(1), 60–70.
Wandsnider, L., 1997. The roasted and the boiled: food composition and heat treatment with special emphasis on pit-hearth cooking. *Journal of Anthropological Archaeology*, **16**(1), 1–48.
Wolynec, R. B., 1977. *The Systematic Analysis of Features from the Koster Site: A Stratified Archaic Site*. Unpublished PhD Dissertation, Evanston, Illinois, Department of Anthropology, Northwestern University.
Wrangham, R., 2009. *Catching Fire: How Cooking Made Us Human*. New York: Basic Books.
Yu, Pei-Lin, 2006. *Pit Cooking and Intensification of Subsistence in the American Southwest and Pacific Northwest*. Unpublished PhD Dissertation, Dallas, Texas, Department of Anthropology, Southern Methodist University.
Zerboni, A., 2011. Micromorphology reveals in situ Mesolithic living floors and archaeological features in multiphase sites in central Sudan. *Geoarchaeology*, **26**(3), 365–391.

Cross-references

Fourier Transform Infrared Spectroscopy (FTIR)
Ground-Penetrating Radar
Hearths and Combustion Features
Magnetometry for Archaeology
Optically Stimulated Luminescence (OSL) Dating
Organic Residues
Paleodiet
Paleomagnetism
Site Formation Processes

C

CACTUS HILL, VIRGINIA

Daniel P. Wagner
Geo-Sci Consultants LLC, University Park, MD, USA

Cactus Hill is an archaeologically stratified, multicomponent site discovered in 1993 on an interior coastal plain terrace adjacent to the Nottoway River in southeastern Virginia, USA. Utilized by humans over a period of many thousands of years, the site is most known for its buried Paleo-Indian occupations, one of which is indisputably of the Clovis culture and another, lying below the Clovis, interpreted to be of an origin predating Clovis. Several lines of evidence support a pre-Clovis component: (1) A sterile 7–20 cm zone of vertical separation lies between Clovis and underlying pre-Clovis materials; (2) different lithic assemblages are distinguished – imported cryptocrystalline rock types (such as chert and chalcedony) are exclusive to the Clovis level, while locally obtained quartzite was used by the pre-Clovis; (3) a distinctive core blade artifact technology for the pre-Clovis occupation; and (4) ^{14}C charcoal ages of 10,920 BP for the Clovis but as early as 16,670 BP for the pre-Clovis. The pre-Clovis component was subsequently referred to as Blade (McAvoy and McAvoy, 1997).

Because the above evidence argues against a long-held theory that Clovis people were the first inhabitants of the Americas, the Blade component became the focus of critical attention. Beyond the theoretical conception was a speculation that the sandy composition of Cactus Hill's dunal soil may have been too unstable to preserve very old cultural materials in an ordered stratified sequence. Multidisciplinary geoarchaeological investigations were employed to address this concern. Pedological investigations (Wagner and McAvoy, 2004) recognized episodic sand deposition but also identified preserved buried surface horizons both at the Clovis level and a deeper, much earlier one (19,540 ^{14}C BP) predating all site occupations. These surfaces and strongly developed, very old subsoil lamellae demonstrated intervals of prolonged stasis and soil formation as well as mostly protective burial during deposition events. Similarly, micromorphological examinations of soil matrices (Macphail and McAvoy, 2008) convincingly showed that Blade artifacts were unlikely to have been emplaced by a process of downdrift from the Clovis level. While relic surface horizon microaggregates were identified at both the Clovis and Blade levels, comparable surface indicators were not present within the intervening culturally sterile zone. In further support, luminescence dating (Feathers et al., 2006) of principal strata was in close agreement with radiocarbon ages and also verified an ordered vertical progression of increasing age with depth. Taken together, the above data indicate that natural soil disturbances such as deflation or mixing appear to have been relatively limited and not likely to have appreciably affected the long-term integrity of site stratigraphy.

Bibliography

Feathers, J. K., Rhodes, E. J., Huot, S., and McAvoy, J. M., 2006. Luminescence dating of sand deposits related to late Pleistocene human occupation at the Cactus Hill Site, Virginia, USA. *Quaternary Geochronology*, **1**(3), 167–187.

Macphail, R. I., and McAvoy, J. M., 2008. A micromorphological analysis of stratigraphic integrity and site formation at Cactus Hill, an early Paleoindian and hypothesized pre-Clovis occupation in south-central Virginia, USA. *Geoarchaeology*, **23**(5), 675–694.

McAvoy, J. M., and McAvoy, L. D., 1997. *Archaeological Investigations of Site 44SX202, Cactus Hill, Sussex County, Virginia*. Richmond, VA: Virginia Department of Historic Resources. Research Report Series, Vol. 8.

Wagner, D. P., and McAvoy, J. M., 2004. Pedoarchaeology of Cactus Hill, a sandy Paleoindian site in Southeastern Virginia, USA *Geoarchaeology*, **19**(4), 297–322.

A.S. Gilbert (ed.), *Encyclopedia of Geoarchaeology*, DOI 10.1007/978-1-4020-4409-0,

CANALS AND AQUEDUCTS IN THE ANCIENT WORLD

Charles R. Ortloff
CFD Consultants International, Ltd., University of Chicago, Los Gatos, CA, USA

Introduction

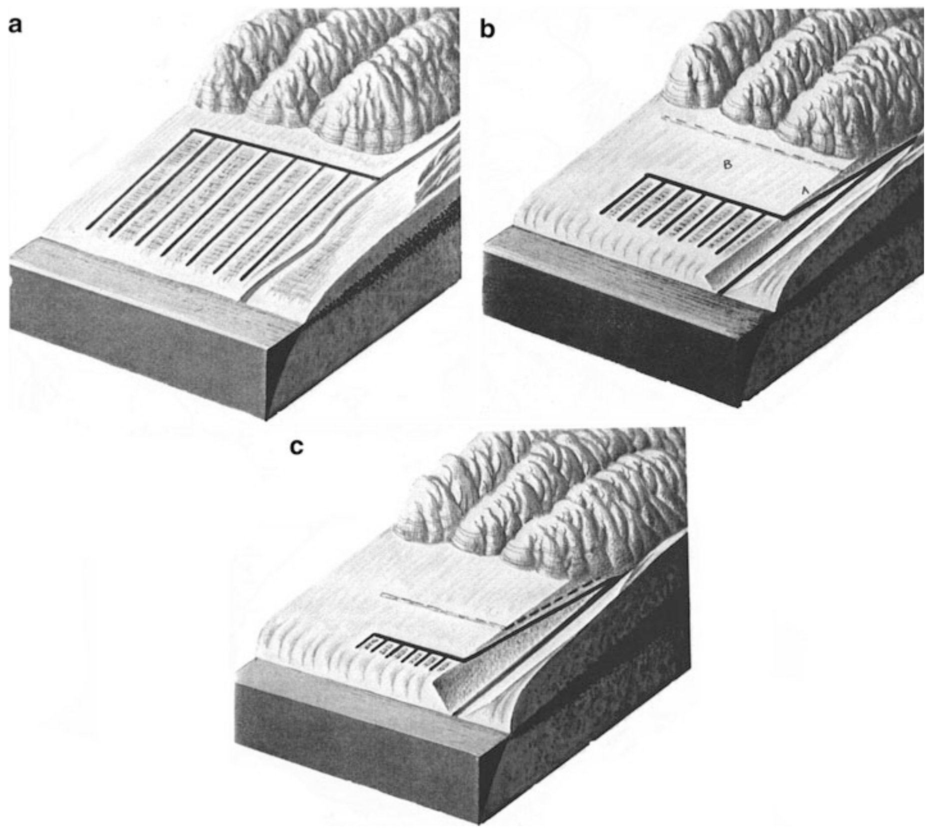
People of the ancient world understood that geophysical and climatic anomalies could alter the environments that permitted the growth of comestible agricultural resources for urban and rural populations. When their technical capability proved adequate, they were able to modify water supply systems to sustain agricultural productivity through times of environmental change. When technological solutions or adaptations to other resources were not possible, societal transformation and/or collapse followed, leaving archaeological remains that now testify to the lack of appropriate technology, management, or manpower to overcome the deteriorating resource base. Water for urban and agricultural use is vital to sustainability. When the collapse of agricultural systems is manifest in the archaeological record, remains of canals, aqueducts, water storage, and transport systems provide vital geoarchaeological clues detailing how and why failure occurred. These clues often point to long-term drought that limited water availability for farming, floods that incurred changes in agricultural landscapes through soil erosion or aggradation, seismic/tectonic effects that disrupted canal and aqueduct systems, river downcutting (rejuvenation) that stranded canal inlets, and aeolian soil transport that led to landscape inflation or deflation processes. The influence of these geoarchaeological processes on water supply and distribution systems is basic to (1) understanding the fate of ancient sites and cultures and (2) interpreting the processes of societal collapse and transformation.

Geoarchaeological effects on canals in ancient South America

Research on ancient canals of pre-Columbian Peru has shown the influence of seismic distortion and tectonic uplift on once-functional canals. Many ancient canals built during the Late Intermediate Period (LIP 800–1480 CE) Chimu occupation of North Coast Peru (Moseley, 2001) show layered silt deposits indicative of the functional, negative-declination slopes necessary to conduct water from rivers through irrigation canals onto field systems. Several major irrigation and water transport canals were subsequently rendered nonoperational by tectonic/seismic effects during the Chimu occupation within the Moche Valley heartland (Ortloff et al., 1985; Ortloff, 2009), thereby severely compromising the intravalley canal network supporting the agricultural field systems vital to maintaining large population centers. A further effect from tectonic uplift was incisive downcutting (rejuvenation) of the Moche River, the main water source for the Moche Valley irrigation network. In addition to uplift, erosion

Canals and Aqueducts in the Ancient World, Figure 1 Downcut riverbank sidewall from the effects of Moche River rejuvenation; the riverbank profile contains artifacts from the Early through Late Intermediate Period (300 BCE–1400 CE) (From Ortloff, 2009: Figure 1.1.12, p. 30).

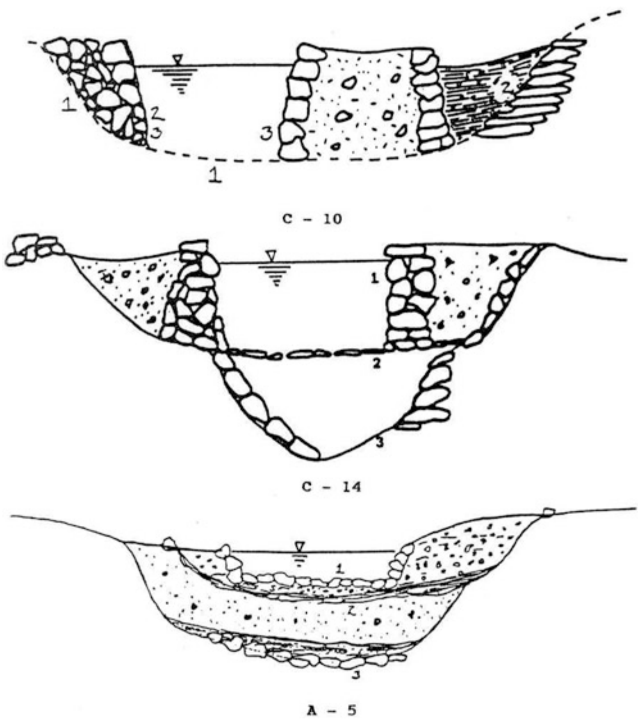
from torrential rains deriving from episodic El Niño events also accelerated the downcutting processes. The river gradually deepened its bed relative to the adjacent land surface that contained the agricultural field systems (Whitten and Brooks, 1982). Figure 1 shows the south-side riverbank of the steeply downcut Moche River layered with Early Intermediate Period (EIP 300 BCE–600 CE) cultural remains indicating the effects of river downcutting episodes that began in earlier EIP and continued through the later LIP Chimu occupation. Fed by flow from seasonal Andean mountain rainfall runoff, the Moche River deepened its bed in step with tectonic uplift, leading over time to lowered water levels and the stranding of inlets to irrigation canals originating in valley neck areas far from the coastline. These inlets served field systems on the coastal plains and were eventually abandoned when they became nonfunctional. As canals with valley neck inlets were abandoned, new canals were constructed further downriver toward the coast in places where downcutting was as yet minimal. These new constructions required short canals with shallow slopes that



Canals and Aqueducts in the Ancient World, Figure 2 Graphic representation of downcutting evolution in the Moche River: *frames A, B*, and *C* represent sequential riverbed lowering producing loss of agricultural land as canal inlets are stranded and tapping of river water progressively upriver limits the acreage that can be brought under cultivation (From Ortloff, 2009: Figure 1.1.13, p. 32).

were built into riverbank sidewalls to conduct water from the level of the river to slightly lower canal inlets serving lower elevation field systems. With ongoing tectonic uplift and river downcutting over many centuries, and with new canal inlets being constructed as higher elevation inlets were abandoned, agricultural field area was compressed into ever-decreasing areas downriver from the older abandoned inlets. This process is illustrated by the inlet/canal sequencing shown in Figure 2. Thus, geophysical processes acting on canal-based irrigation agriculture were a factor contributing to the ultimate collapse of the Chimu Moche Valley irrigation system in the tenth to eleventh centuries CE.

Coincident with these ongoing geophysical effects, long-term drought (Thompson et al., 1985, 1995) in Peru from ~1000 to 1300 CE lowered river flow rates and thereby compromised the water supply available for agriculture. A typical Chimu Moche Valley canal serving the Pampa Huanchaco field system (Ortloff, 2009) exhibited cross-section profiles that showed continual modification to accommodate decreasing water flow rates (Figure 3). Low Moche River water supplies impacted agricultural production severely, which then failed to support the large Chimu population at the Moche Valley Chimu capital city of Chan Chan. A remedial measure was attempted in order to overcome the decline in agricultural production: the 75 km Intervalley Canal was constructed prior to ~1000 CE to bring water from the higher flow rate river in the adjacent Chicama Valley to resuscitate failing Moche Valley field systems (Ortloff et al., 1982). Another remedial measure was the extensive excavation of deep pits dug to the phreatic zone of the water table near the Pacific coast margin of Chan Chan, also to maintain limited agricultural production. The Intervalley Canal's hydraulic design was ingeniously crafted to produce a maximum flow rate to match and reactivate the Moche Valley's main intravalley Vichansao distribution canal and provide water to field systems along its route to the Moche Valley (Ortloff et al., 1982; Ortloff, 2009); however, it stretched the drought-limited water supply of the Chicama River and ultimately provided only a short-lived solution to reactivate desiccated branch canals and maintain Moche Valley agriculture. Evidence of path modifications to restore functionality to the Intervalley Canal attest to seismically induced landscape distortions affecting canal slopes during its period of use; ultimately the combination of long-term drought and seismic distortions rendered the canal unusable. While the cumulative effects from



Canals and Aqueducts in the Ancient World, Figure 3 Cross-section profiles of a canal from the Pampa Huanchaco area of the Moche Valley; profiles indicate continuous infilling and contraction of cross sections as tenth- to eleventh-century drought reduced water supply to canals (From Ortloff, 2009: Figure 1.1.8, p. 25).

centuries of climatic and geomorphic change steadily contracted the heartland of Moche Valley agriculture, the Chimu expanded into north coast valleys with richer water and land resources in later times.

The Late Preceramic (2600–1800 BCE) society at Caral, located in the Supe Valley of coastal Peru, is a further example of geophysical landscape changes influencing both agricultural productivity and the marine resource base underwriting their economies. With intensifying ENSO (El Niño-Southern Oscillation) floods occurring at this time (Sandweiss et al., 2009), flood sediment transport produced large offshore beach ridges that trapped flood sediments, infilled bays with marshes, and prograded earlier shoreline locations by flood sediment deposition and aeolian sand transport (Ortloff, 2009; Sandweiss et al., 2009; Ortloff, 2012). These geophysical processes gradually buried extensive coastal agricultural field systems in the valley delta area and caused agriculture to be transferred to narrow and distant up-valley farming areas that were insufficient to support the large valley population. ^{14}C dating of near-shoreline-habitat mollusk deposits, now far inland from the present-day shoreline (Figure 4), indicates that large-scale sediment transport and littoral infilling had occurred over centuries (Ortloff, 2012). These episodes buried coastal agricultural fields beneath non-fertile sands and gravels that derived from concentrated ENSO flood events, preventing agriculture from being reestablished. Supe Valley excavation pits ~3 km inland reveal 4–5 m of sediment deposits covering what was previously Holocene beach sands. As sediment deposits and clay banks accumulated behind the beach ridges, decreased coastal zone hydraulic conductivity resulted, creating limited groundwater drainage. This caused the water table to back up and rise, producing up-valley bottomland springs in narrow valleys. These springs were canalized to support limited, narrow-valley bottomland field systems and ramped aqueduct canals built along the south-side Supe Valley canyon walls supplied by bottomland springs from far up-valley sources. The ramped canals led water to plateau field areas that added limited agricultural field acreage. Up-valley agricultural bottomlands were subject to episodic El Niño erosive flood events that reduced land areas suitable for agriculture and further destabilized the economic base of valley population centers. The major loss of large coastal fields buried by flood sediments, however, made it difficult to sustain all 19 Supe Valley sites, and their populations as geophysical landscape change progressed. Again, geophysical processes played a prominent role in influencing site abandonment of Preceramic societies in the Supe and adjacent coastal valleys. All sites were eventually abandoned by 1800 BCE, presumably due to the large-scale geophysical effects that compromised their economic base founded upon trade of marine resources from coastal sites for agricultural resources from inland sites (Shady Solís, 2000, 2007). As the marine resource base (primarily shellfish gathering) was compromised by bay infilling and the agricultural area underwent progressive contraction, the sustainability of coastal Late Preceramic society's economic base decreased.

The Middle Horizon (300 BCE–1100 CE) site of Tiwanaku (Bolivia) also underwent a collapse due to long-term drought in the tenth to eleventh centuries. A dropping water table and declining spring flow ultimately stranded 100,000 km^2 of raised field systems adjacent to Lake Titicaca that supported agriculture for the Tiwanaku capital city (Ortloff and Kolata, 1993); no ^{14}C dates indicating occupation after 1100 CE are recorded for the capital city or satellite centers.

Ancient South American societies experienced a variety of climatic effects that induced geophysical landscape changes affecting their agricultural and marine resource base. The disappearance and/or transformation of major societies, and their resurrection under different social structures in different areas when drought conditions relaxed in the twelfth to thirteenth centuries CE, depended largely upon exploitation of more sustainable agro-systems that benefitted from increasing water resources. Colonies and satellite settlements characterized many major Andean societies (Murra, 1962). This strategy expanded agriculture into different ecological zones and applied different farming techniques, employing local

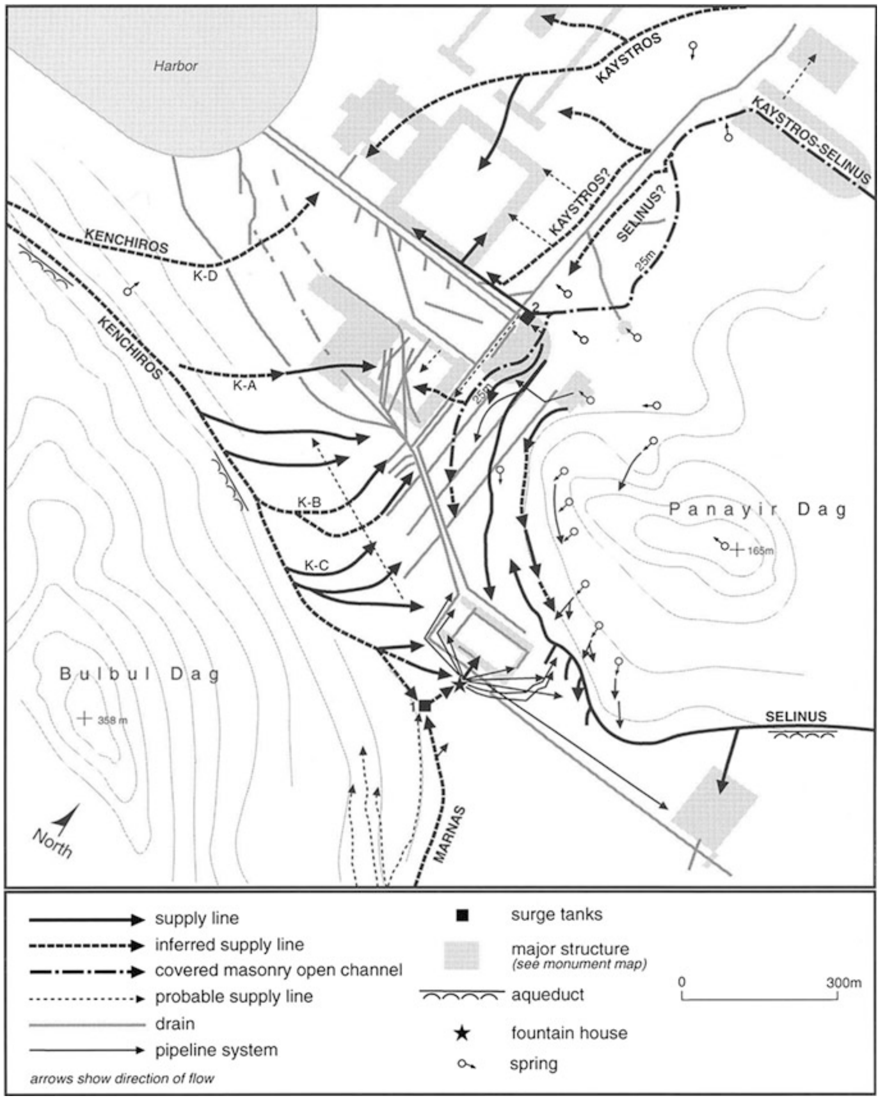
Canals and Aqueducts in the Ancient World, Figure 4 ^{14}C dates from mollusk layer concentrations far inland from the present-day Pacific Coast shoreline indicating aeolian/flood sediment transport producing coastal infilling over millennia; mollusk species sampled are known to thrive in ~1 m seawater. Samples obtained surrounding the salt pans of Salinas de Huacho, north of Lima, Peru.

water resources to lessen the dependence upon a single agro-system type. This approach proved valuable in diversifying the agricultural resource base of Andean societies.

Geoarchaeological effects on societies of the ancient Middle East

While climate change and severe weather events characterize coastal and highland societies of ancient (and modern) South America due to ENSO El Niño and La Niña drought and flood effects, ancient (and modern) Mediterranean societies had the advantage of milder climate and fewer significant weather fluctuations. For the most part, Roman, Greek, and Levantine civilizations experienced fewer climate-related environmental challenges than their South American counterparts. While drought and flood events certainly occurred, colonies and captive areas under central state authority that encompassed vastly different ecological zones guaranteed a resource base available through trade and tribute to sustain the large populations of capital cities. Under stable climate/weather conditions, canal and aqueduct construction exhibited a degree of permanence that reflected the monumental labor input dedicated to their construction. This is in contrast to ancient South American societies whose survival and continuity depended upon water transport and agricultural systems that had to be modified to accommodate changing ecological conditions.

As an example, consider the case of Roman Ephesus (Turkey) and the engineering that characterized the permanent water distribution structures constructed without major interferences from the effects of climate or other geophysical change (Bammer, 1988; Scherrer, 1995; Ortloff and Crouch, 2001; Crouch, 2004; Ortloff, 2009). Water supply to the city was by means of canals and aqueducts from distant spring systems (Figure 5); the terminal point for aqueduct flows was a multi-chambered holding tank structure (castellum), each of whose chambers held water at different depths, a condition that determined the hydraulic pressure and flow rate from each chamber into pipes that emerged from the base of individual chambers.



Canals and Aqueducts in the Ancient World, Figure 5 Water supply and drainage lines for Ephesus in the Roman occupation period (From Ortloff, 2009: Figure 2.3.8, p. 313).

The water distribution system consisted of joined segments of terracotta piping running from individual castellum chambers to city destination points, each with given water requirements. Other water distribution components consisted of open channels that led directly from a castellum to reservoirs and then to pipe systems that supplied baths, elite housing compounds, administrative structures, marketplace areas, fountains, and latrines within the city. When open channels were impractical due to access or unstable landscape paths, buried multiple pipeline bundles were used. Pipeline systems buried at shallow depths had the advantage of being conveniently reparable, as broken segments could easily be replaced. Open channels likewise had easy repair access. When earthquake damage occurred, repairs could be readily conducted. Thus, few elaborate renovation mechanisms were needed as repairs were made by virtue of the simplicity and accessibility of near-surface water piping networks. Drainage from built structures and baths was through subterranean channels that drained into the nearby bay. Rainfall runoff was collected through gaps in street paving slabs and conducted directly to the bay. Thus, both water supply and drainage facilities could be readily repaired due to the nature of the design. Large aqueduct structures were able to resist seismic loading pulses due to the flexibility provided by non-mortared, stone block construction that distributed and dissipated energy through sliding friction between the many individual blocks forming the aqueduct. While this type of construction limited earthquake damage, it is questionable whether this was a thoughtful consideration in Roman construction methodology. It produced a fortuitous outcome nonetheless. Redundancy was built into the water supply to the city by five different aqueducts from different springs (Figure 5). Although most components of the Ephesian water system were resistant to moderate seismic loading due to their flexibility and ease of repair, Ephesus nevertheless was vulnerable to some geophysical risk brought about by its location adjacent to major rivers that carried the large volumes of rainfall runoff (silt and sand) that are characteristic of the mountainous coastal zone of western Turkey. Silt from runoff erosion of mountain soils carried by the Meander (Büyük Menderes) River over many centuries gradually infilled the bay adjacent to the city (Kraft et al., 1999) and reduced the maritime trade and commercial importance of Ephesos. These river silts deposited ~10 m of sediments and engulfed an earlier Greek settlement below Roman Ephesus, thereby covering sacred processional paths associated with the earlier Greek settlement and burying springs at the base of the largely karst composition mountain (Crouch, 2004) adjacent to the Roman city precincts.

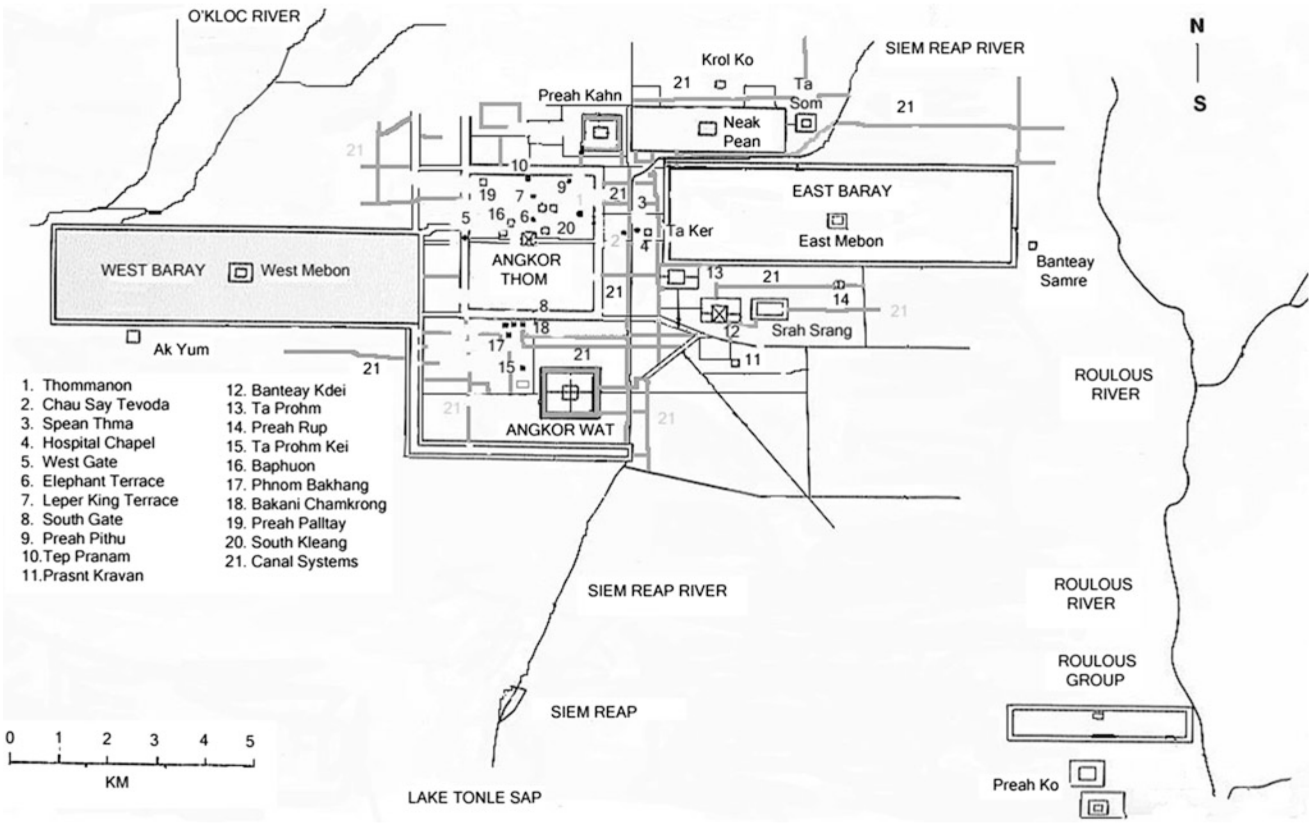
At Ephesus, canal and aqueduct systems leading from mountain spring sources distributed water into the urban core through complex pipeline systems that supplied water for 250,000 inhabitants at 150 gal/day/person, including baths, fountains, nymphea, latrines, elite housing compounds, public buildings, a coliseum, gymnasia, and a theater, all of which required a continuously running water supply (Figure 5). The nearby Temple of Artemis, originally ~3 km inland from the Mediterranean shoreline, was served by multiple underground pipelines of different designs for different ceremonial uses (Ortloff, 2009). This site, originating around 800 BCE, became inundated after many centuries of operation as a result of coastal subsidence and progradation, uplift of inland mountains, and sediment deposits interfering with springs that supplied water to the temple. Here, the geophysical effects were so gradual and subtle that compensatory structural engineering considerations made in advance of construction were apparently not a major concern.

The site of Petra in Jordan (Bourbon, 1999; Taylor, 2001; Guzzo and Schneider, 2002) is a further example of the creative use of intermittent water supplies from rainfall and springs to maintain city activities over centuries. Spring systems within tens of kilometers of Petra provided water to reservoirs from which terracotta pipes guided the flow to inner urban precincts for agoras, fountains, theater, water gardens, temples, public buildings, and domestic housing. Piping systems of different hydraulic designs were necessary given how distant these springs were from distribution hubs. Known from ancient times, and verifiable from modern computer calculations, is that a linear increase in supply hydraulic head does not result in a corresponding linear flow rate increase in long pipelines (Ortloff, 2009) due to nonlinear, cumulative water-internal pipe wall friction effects. This design constraint, together with how landscape-governed slope variations place constraints on pipe flow rate, results in a catalogue of hydraulic designs (Ortloff and Kassinos, 2003; Ortloff, 2009) that were utilized at Petra for the Siq, Jebel el Kubtha, and Zurraba water supply systems. Such urban core water supply systems possessing different hydraulic solutions for different geophysical constraints demonstrate that the ancient engineers possessed a wide knowledge base, approaching in many cases that of modern hydraulic design practice. Rainfall catchment basins and reservoirs provided additional water supplies and limited runoff into the urban center; some 250 such basins have been located in the mountainous areas surrounding Petra. The predictability of rainfall periods in this area of Jordan was well understood in antiquity and served to provide city reservoirs with water through many catchment basins and springs. Defensive water diversion channels and dams limited water damage to the urban core of Petra; here knowledge of water control was key to the permanence of the city for many centuries.

For the sites mentioned, the permanence of construction of fixed water supply elements (canals, pipelines, aqueducts, and reservoirs serving city and agricultural systems) indicates that geophysical threats were minimal outside of occasional, but reparable, earthquake damage. Thus, with regard to water supply systems, the advantage of the Mediterranean world with its stable climate and weather norms is apparent compared to New World cities and settlements.

Geophysical effects on the water systems of the Khmer Kingdom city of Angkor

The site of Angkor (800–1450 CE) in central Cambodia (Laur, 2002; Coe, 2003) reveals a long history of innovative water management that supported agricultural resources for a vast population centered about the central city core. A series of moats, channels, reservoirs, dams, and ritual water healing centers characterized the city's precincts (Figure 6). Of interest are two large reservoirs (*barays*), the largest of which is the West Baray with an 8×5 km footprint. A wide-barrier dike enclosed the baray on all sides, and water from monsoon rainfall and the Puok and Siem Reap rivers provided water to fill the reservoir during the rainy season. While some release points along the dike led to irrigation canals, the large reservoir had a profound reason for its existence. Groundwater flow modeling (Ortloff, 2009) indicates that water stored in the reservoir during dual monsoon seasons was slowly released by groundwater seepage during the dry season to maintain a constant groundwater height throughout the year in areas south and east of the baray. The area between the baray and the edge of Lake Tonlé Sap was primarily for rice cultivation in sunken pits dug below the water table. The East Baray served a similar function by maintaining groundwater height under the city's urban core and keeping the water level in moats and ceremonial pools constant year-round. Without dry season groundwater recharge from the barays, a permanent collapse in subsoil porosity would have occurred causing ground subsidence and structurally compromising the Angkor temples. Thus, two major barays, together with reservoirs,



Canals and Aqueducts in the Ancient World, Figure 6 Site feature map of Angkor (Cambodia) (From Ortloff, 2009: Figure 3.1.1, p. 359).

pools, and moats within city precincts, served to maintain the structural integrity of the many temples of Angkor, permitted extension of rice cropping on a year-round basis, and provided aesthetic embellishment to the Khmer version of the celestial capital of the gods. Through captured monsoon runoff, groundwater seepage systems, and surface transfer canals, an elaborate three-dimensional water control system (subsurface and surface) gave prosperity and continuity to Angkor over many centuries of occupation. Thus, Khmer knowledge of geophysical effects related to groundwater movement was a vital element in their city's prominence over many centuries.

Southwestern Native American societies: geophysics of canals and aqueducts

Over geologic epochs spanning millions of years, the Colorado Plateau has been etched by the deepening and headward extension of innumerable small valleys opened during periods of intermittent heavy rainfall. These valleys are characterized by floodplain incision from rain runoff producing areas of unconsolidated sediment deposits within the valleys that limit water control for irrigation agriculture (Longwell and Flint, 1962; Cooke and Reeves, 1976). Heavy rains lead to sediment deposition over bedrock, creating arable land for irrigation agriculture but not in areas prone to periodic erosion. Farther south in the Basin and Range country, deeper alluvial valleys containing sandy desert soils limit agricultural productivity due to limited moisture retention, as well as climate/weather conditions characterized by high desert temperatures and more frequent drought conditions. Across the Southwest, many alluvial valleys are prone to stream entrenchment (arroyo cutting) that lowers water tables and restricts the amount of arable land that can be irrigated (Cooke and Reeves, 1976). Thus, as a result of heavy flood runoff and periodic droughts, agriculture was limited by both climate and geomorphic processes that placed constraints on water control.

Yet despite difficulties with unstable farming terrains in these geographic zones, Spanish settlers coming into the area post-1540 CE found land being productively farmed by indigenous peoples (Doolittle, 2000) who ingeniously modified the landscape to capture and store intermittent rainfall and snowmelt to sustain crops (Anschuetz, 2001, 2006; Plog, 2008). On the Colorado Plateau, for example, most of the agriculture noted by the Spanish was floodwater farmed. Periods of drought that deteriorated grasslands and amplified erosion during heavy rainstorms, together with periods of light, but more frequent, rains caused continuous infilling of valleys with alluvium. Farming required adaptive responses to prehistoric climate variability influenced by El Niño and La Niña rainfall and drought periods, respectively (Dean and Robinson, 1977; Fish and Fish, 1984; Doolittle, 1992; Damp et al., 2002). Several of the major prehistoric (pre-Columbian) Indian societies of the Colorado Plateau (e.g., Anasazi and Mogollon) and southern Basin and Range areas outside of the Plateau (e.g., Hohokam and Patayan) farmed floodplains watered by melting winter snow and summer rains. Additional hill-slope terracing was used to stabilize planting surfaces, and flood diversion dams were built to limit erosional/depositional effects on field plots (Doolittle, 1992; Lightfoot and Eddy, 1995; Doolittle, 2000; Anschuetz, 2001).

Diverse technical innovations founded upon highly evolved indigenous cultural knowledge allowed for successful crop production in distinct geomorphic settings (Woosley, 1980; Doolittle, 1992, 2000). For example, the prehistoric Puebloans (Anasazi) located on Mesa Verde in Colorado (Ferguson, 1996) constructed a series of four reservoirs (Box Elder, Morefield, Far View, and Sagebrush) that were operational from 750 to 1180 CE and captured rainfall runoff to redistribute water for agricultural and domestic use (Leeper, 1986; Wilshusen et al., 1997; Wright, 2003). Ethnographically, the Tewa of north-central New Mexico employed bermed terraces to capture rainfall, together with stone-lined transport canals, dams, and spreaders to capture (or divert) runoff. The Tewa could exploit a combination of direct precipitation, intermittent runoff, groundwater, and canal extraction from springs and rivers to water their fields (Doolittle, 1992, 2000; Anschuetz, 2001, 2006). Stone-mulched and stone-bordered sunken pits were also used by Pueblo society to trap precipitation. Anschuetz (2001, 2006) describes anecdotal evidence that winter snow was rolled into balls and deposited in these pits in order to store water and amplify soil moisture for later agricultural use. The Hohokam (600–1350 CE) of south-central Arizona utilized extensive canal networks drawn from rivers and springs to irrigate vast field areas. The Salt River Valley contained as many as 400 km of main and distribution canals (Howard, 1987; Doolittle, 2000; Plog, 2008) with the Gila and Verde Valleys containing yet more irrigation canals estimated to be on the order of 600 km in cumulative length.

South-central Arizona employed the greatest extent of canal irrigation compared to all other southwestern indigenous societies. Aerial photography of these prehistoric canal and field system complexes taken 80 years ago (Judd, 1930) has proven indispensable in discovering and documenting trace canal, and field system remains now obliterated by erosion, sediment deposition overlays, and modern agriculture proceeding from urban expansion. Canal water transport technologies practiced by the Pima (Akimel O'odham) along the Gila River involved long, low-slope, open channels that supplied field systems. While similar water control systems were used elsewhere in the Southwest, canals originating from smaller river tributaries to major rivers were a preferred strategy due to easy water control practices. Other agricultural practices depended upon floodwater farming, especially in areas lacking large, perennial rivers. For example, the Papago (Tohono O'odham) were known for their *ak chin* (floodwater) farming along ephemeral streams, while the Navajo and Hopi planted fields in drainage areas where floods and runoff occurred during heavy rains (Plog, 2008). Further innovative indigenous agricultural strategies practiced in the Southwest are summarized by Doolittle (2000) and Plog (2008).

Modern scientific techniques integrated into archaeological studies add greatly to our understanding of complex geomorphologic processes and the response of indigenous societies to challenges posed by climate and landscape limitations. For example, ^{14}C and luminescence dating (Berger et al., 2009; Watkins et al., 2011), as well as pollen and biometric analysis of sediment layers in canals and reservoirs, provides insight into age, use history of water control features (Huckleberry, 1999; Wright, 2003; Wright et al., 2005; Wright, 2006), and an understanding of crop types farmed by different societies. Additionally, much has been learned about prehistoric canals and fields through analysis of the physical-mechanical properties of sediments and alluvial deposits (hydraulic conductivity, porosity, stratigraphy). These studies provide insight into rain infiltration and seepage rates, as well as details illuminating the formation processes of canals and reservoirs. For example, sedimentological and stratigraphic analyses of Anasazi mesa top and valley water storage reservoir systems and canals were essential to understanding their role in sustaining local farming communities (Rohn, 1977; Wright, 2003; Wright et al., 2005; Wright, 2006). Application of concepts from fluvial geomorphology (Knighton, 1998) (e.g., erosion initiation, sediment transport and deposition) has proven useful in recognizing the impacts of floods and climate change on indigenous farming in the American Southwest (Cooke and Reeves, 1976; Bettess and White, 1983; Abrahams, 1987), as well as post-abandonment weathering of agricultural landscapes. When combined with dendrohydrological studies (Dean and Robinson, 1977), fluvial geomorphic analysis provides insight into how indigenous Southwestern societies changed their irrigation strategies (which are detectable from archaeological studies) as an adaptation to climate and landscape changes.

Conclusions

A survey of urban/agricultural water supply systems of major New and Old World societies on four regions of the world reveals exploitation of different varieties of water sources available in different ecological zones. Dams, reservoirs, canals, aqueducts, pipelines, open channels, and groundwater resources served to collect, transport, and distribute water to urban centers and agricultural fields. Each water system type with its selection of water transport and storage systems exhibited vulnerabilities when subject to climate and geophysical landscape changes. When system modifications were not possible due to insufficient technology, labor shortage, or lack of management expertise, societies underwent collapse, transformation, and altered societal and cultural trajectories as observed in the archaeological record. Differences exist between water transport and distribution systems employing different construction techniques and materials by New and Old World societies. Where the effects of climate and geophysical landscape change were minimal over long time periods, construction was permanent and alterations remedial in nature; where climate and weather patterns were changeable and affected the stability of water transport systems, flexibility of design and modification is evident to guarantee sustained use of these water systems. Examples discussed reveal this basic strategy difference between Old and New World societies. The many different water usage strategies employed by these societies constitute a virtual library of solutions tailored to different ecological and geomorphic conditions and provide insight into the creativity and resourcefulness of ancient engineers to maintain their communities despite changes in environmental conditions affecting their agricultural resource base.

Bibliography

Abrahams, A. D., 1987. Channel network topology: regular or random? In Gardiner, V. (ed.), *International Geomorphology, 1986: Proceedings of the First International Conference on Geomorphology, Part II*. Chichester: Wiley, pp. 145–158.

Anschuetz, K. F., 2001. Soaking it in: Northern Rio Grande Pueblo lessons in water management and landscape ecology. In Weinstein, L. L. (ed.), *Native Peoples of the Southwest: Negotiating Land, Water, and Ethnicities*. Westport: Bergin & Garvey, pp. 49–78.

Anschuetz, K. F., 2006. Tewa fields, Tewa traditions. In Price, V. B., and Morrow, B. H. (eds.), *Canyon Gardens: The Ancient Pueblo Landscapes of the American Southwest*. Albuquerque: University of New Mexico Press, pp. 57–74.

Bammer, A., 1988. *Ephesos: Stadt an Fluss und Meer*. Graz: Akademische Druck- u. Verlagsanstalt.

Berger, G. W., Post, S., and Wenker, C., 2009. Single and multigrain quartz-luminescence dating of irrigation channel features in Santa Fe, New Mexico. *Geoarchaeology*, **24**(4), 383–401.

Bettess, R., and White, W. R., 1983. Meandering and braiding of alluvial channels. *Proceedings of the Institution of Civil Engineers*, **75**(3), 525–538.

Bourbon, F., 1999. *Petra: Art, History and Itineraries in the Nabataean Capital*. Vercelli: White Star.

Coe, M. D., 2003. *Angkor and the Khmer Civilization*. New York: Thames and Hudson.

Cooke, R. U., and Reeves, R. W., 1976. *Arroyos and Environmental Change in the American South-West*. Oxford: Clarendon.

Crouch, D. P., 2004. *Geology and Settlement: Greco-Roman Patterns*. Oxford: Oxford University Press.

Damp, J. E., Hall, S. A., and Smith, S. J., 2002. Early irrigation on the Colorado Plateau near the Zuni Pueblo, New Mexico. *American Antiquity*, **67**(4), 665–676.

Dean, J. S., and Robinson, W. J., 1977. *Dendroclimatic variability in the American Southwest, A.D. 680–1970.* Final Report to the National Park Service, Department of the Interior. Tucson: Laboratory for Tree-Ring Research.

Doolittle, W. E., 1992. Agriculture in North America on the eve of contact: a reassessment. *Annals of the Association of American Geographers*, **82**(3), 386–401.

Doolittle, W. E., 2000. *Cultivated Landscapes of Native North America*. New York: Oxford University Press.

Ferguson, W. M., 1996. *The Anasazi of Mesa Verde and the Four Corners*. Niwot: University Press of Colorado.

Fish, S. K., and Fish, P. R., 1984. *Prehistoric Agricultural Strategies in the Southwest*. Tempe: Arizona State University. Anthropological Research Papers, Vol. 33.

Guzzo, M. G. A., and Schneider, E. E., 2002. *Petra*. Chicago: The University of Chicago Press.

Howard, J. B., 1987. The Lehi Canal System: organization of a Classic Period community. In Doyel, D. E. (ed.), *The Hohokam Village: Site Structure and Organization*. Glenwood Springs: American Association for the Advancement of Science, pp. 211–222.

Huckleberry, G., 1999. Assessing Hohokam canal stability through stratigraphy. *Journal of Field Archaeology*, **20**(1), 1–18.

Judd, N. M., 1930. *Arizona Sacrifices her Prehistoric Canals*. Washington, DC: The Smithsonian Press. Explorations and Field-Work of the Smithsonian Institution in 1929.

Knighton, D., 1998. *Fluvial Forms and Processes: A New Perspective*. London: Arnold.

Kraft, J. C., Brückner, H., and Kayan, I., 1999. Paleogeographies of ancient coastal environments in the environs of the Feigengarten Excavation and the 'Via(e) Sacra(e)' to the Artemision at Ephesus. In Scherrer, P., Taeuber, H., and Thür, H. (eds.), *Steine und Wege: Festschrift für Dieter Knibbe zum 65. Geburtstag*. Vienna: Österreichisches Archäologisisches Institut. Sonderschriften 32, pp. 91–100.

Laur, J., 2002. *Angkor: An Illustrated Guide to the Monuments*. Paris: Flammarion.

Leeper, J. W., 1986. A computer model of the Mummy Lake water collection system in the Mesa Verde National Park. In *Proceedings of the 6th Annual American Geophysical Front Range Branch Hydrology Days*. Colorado State University.

Lightfoot, D. R., and Eddy, F. W., 1995. The construction and configuration of Anasazi pebble-mulch gardens in the Northern Rio Grande. *American Antiquity*, **60**(3), 459–470.

Longwell, C. R., and Flint, R. F., 1962. *Introduction to Physical Geology*. New York: Wiley.

Moseley, M. E., 2001. *The Incas and Their Ancestors: The Archaeology of Peru*. London: Thames and Hudson.

Murra, J. V., 1962. Cloth and its functions in the Inca State. *American Anthropologist*, **64**(4), 710–728.

Ortloff, C. R., 2009. *Water Engineering in the Ancient World: Archaeological and Climate Perspectives on Societies of Ancient South America, the Middle East and South-East Asia*. Oxford: Oxford University Press.

Ortloff, C. R., and Crouch, D. P., 2001. The urban water supply and distribution system of the Ionian city of Ephesos in the Roman Imperial Period. *Journal of Archaeological Science*, **28**(8), 843–860.

Ortloff, C. R., and Kassinos, A., 2003. Computational fluid dynamics investigation of the hydraulic behavior of the Roman inverted siphon system at Aspendos, Turkey. *Journal of Archaeological Science*, **30**(4), 417–428.

Ortloff, C. R., and Kolata, A. L., 1993. Climate and collapse: agro-ecological perspectives on the decline of the Tiwanaku State. *Journal of Archaeological Science*, **20**(2), 195–221.

Ortloff, C. R., and Moseley, M. E., 2012. 2600–1800 BCE Caral: environmental change at a Late Archaic Period site in north central coast Peru. *Journal of Andean Archaeology (Ñawpa Pacha)*, **32**(2), 189–206.

Ortloff, C. R., Moseley, M. E., and Feldman, R. A., 1982. Hydraulic engineering aspects of the Chimu Chicama-Moche Intravalley Canal. *American Antiquity*, **47**(3), 572–595.

Ortloff, C. R., Feldman, R. A., and Moseley, M. E., 1985. Hydraulic engineering and historical aspects of the Pre-Columbian Intravalley Canal System of the Moche Valley, Peru. *Journal of Field Archaeology*, **12**(1), 77–98.

Plog, S., 2008. *Ancient Peoples of the American Southwest*, 2nd edn. New York: Thames and Hudson.
Rohn, A. H., 1977. *Cultural Change and Continuity on Chapin Mesa*. Lawrence: The Regents Press of Kansas.
Sandweiss, D. H., Shady Solís, R., Moseley, M. E., Keefer, D. K., and Ortloff, C. R., 2009. Environmental change and economic development in coastal Peru between 5,800 and 3,600 years ago. *Proceedings of the National Academy of Sciences*, **106**(5), 1359–1363.
Scherrer, P., 1995. The city of Ephesos from the Roman period to late antiquity. In Koester, H. (ed.), *Ephesos Metropolis of Asia: An Interdisciplinary Approach to its Archaeology, Religion, and Culture*. Valley Forge: Trinity Press International, pp. 1–25.
Shady Solís, R., 2000. Sustento socioeconómico del estado pristino de Supe-Perú: las evidencias de Caral-Supe. *Revista Arqueología y Sociedad*, **13**, 49–66.
Shady Solís, R., 2007. *The Social and Cultural Values of Caral-Supe, the Oldest Civilization in Peru and the Americas, and Their Role in Integrated and Sustainable Development*. Lima: Instituto Nacional de Cultura.
Taylor, J., 2001. *Petra and the Lost Kingdom of the Nabataeans*. Cambridge: Harvard University Press.
Thompson, L. G., Mosley-Thompson, E., Bolzan, J. F., and Koci, B. R., 1985. A 1500-year record of tropical precipitation in ice cores from the Quelccaya Ice Cap, Peru. *Science*, **229**(4717), 971–973.
Thompson, L. G., Mosley-Thompson, E., Davis, M. E., Lin, P.-N., Henderson, K. A., Cole-Dai, J., Bolzan, J. F., and Liu, K.-B., 1995. Late glacial stage and Holocene tropical ice core records from Huascarán, Peru. *Science*, **269**(5220), 46–50.
Watkins, C. N., Rice, G. E., and Steinbach, E., 2011. Dating Hohokam canals: a methodological case study. *Journal of Arizona Archaeology*, **1**(2), 162–168.
Whitten, D. G. A., and Brooks, J. R. V., 1982. *A Dictionary of Geology*. New York: Penguin.
Wilshusen, R. H., Churchill, M. J., and Potter, J. M., 1997. Prehistoric reservoirs and water basins in the Mesa Verde region: intensification of water collection strategies during the Great Pueblo Period. *American Antiquity*, **62**(4), 664–681.
Woosley, A. I., 1980. Agricultural diversity in the prehistoric Southwest. *The Kiva*, **45**(4), 317–335.
Wright, K. R., 2003. *Water for the Anasazi*. Kansas City: Public Works Historical Society. Essays in Public Works History, No. 22.
Wright, K. R., 2006. *The Water Mysteries of Mesa Verde*. Boulder: Johnson Books.
Wright, K. R., Bikis, E., Wiltshire, R. W., and Pemberton, E., 2005. ASCE recognizes Mesa Verde prehistoric reservoirs. *US Society on Dams Monthly Newsletter*, **136**(July), 8–12.

CASPER SITE, WYOMING

Vance T. Holliday
Anthropology and Departments Geosciences, University of Arizona, Tucson, AZ, USA

The Casper site was a bone bed from a bison kill near Casper, Wyoming. It was destroyed by construction activity shortly after excavations in 1971. The site is on the fourth terrace above the northern bank of the North Platte River and is located near the margin of an extensive dune field that follows the North Platte valley. Geoarchaeological research informed investigators about the setting at the time of occupation and also provided insights into human actions involved in creating the site.

The site was exposed in stratified sands resting on top of Pleistocene gravels that comprise most of the terrace fill. It consisted of the remains of ~100 extinct bison (*Bison antiquus*). Associated with the bones were 60 bifacial Hell Gap projectile points (one of a number of North American Paleoindian projectile point styles), along with unifacial cutting tools, resharpening flakes, and stream-worn cobbles likely used as hammerstones in the butchering process. The site is radiocarbon dated to ~10,000 ^{14}C years BP and is a classic example of a Paleoindian bison kill from the northern Great Plains of North America.

Based on the evidence of sedimentology, stratigraphy, and geomorphology at the site, the bison kill took place within a parabolic sand dune. Resting on the terrace is an older set of well-sorted medium sand dunes with low-angle cross bedding. This older set of sands and the upper terrace alluvium were truncated by erosion that formed a long trough that was minimally ~100 m long, ~25 m wide, and 2 m deep. Inset against this elongate depression was another set of medium sand dunes, similarly cross-bedded. The bone bed was in the younger sand deposit, scattered along the paleo-depression. The sedimentology and paleo-topography are essentially identical to the interior of parabolic dunes in the area, where the dune forms with its curved arms upwind and the windward face becomes concave as its surface sand is blown up and over the dune ridge. The interpretation is that bison were driven into the blowout of a parabolic dune. The steep blowout walls of the windward slope trapped or at least slowed the animals so they could be killed. The zooarchaeology combined with the microstratigraphy indicated that the site represented a single event and incorporated both a kill and a processing area.

Bibliography

Albanese, J., 1974. Geology of the Casper archaeological site. In Frison, G. C. (ed.), *The Casper Site: A Hell Gap Bison Kill on the High Plains*. New York: Academic, pp. 173–190.
Frison, G. C. (ed.), 1974. *The Casper Site: A Hell Gap Bison Kill on the High Plains*. New York: Academic.

Cross-references

Great Plains Geoarchaeology

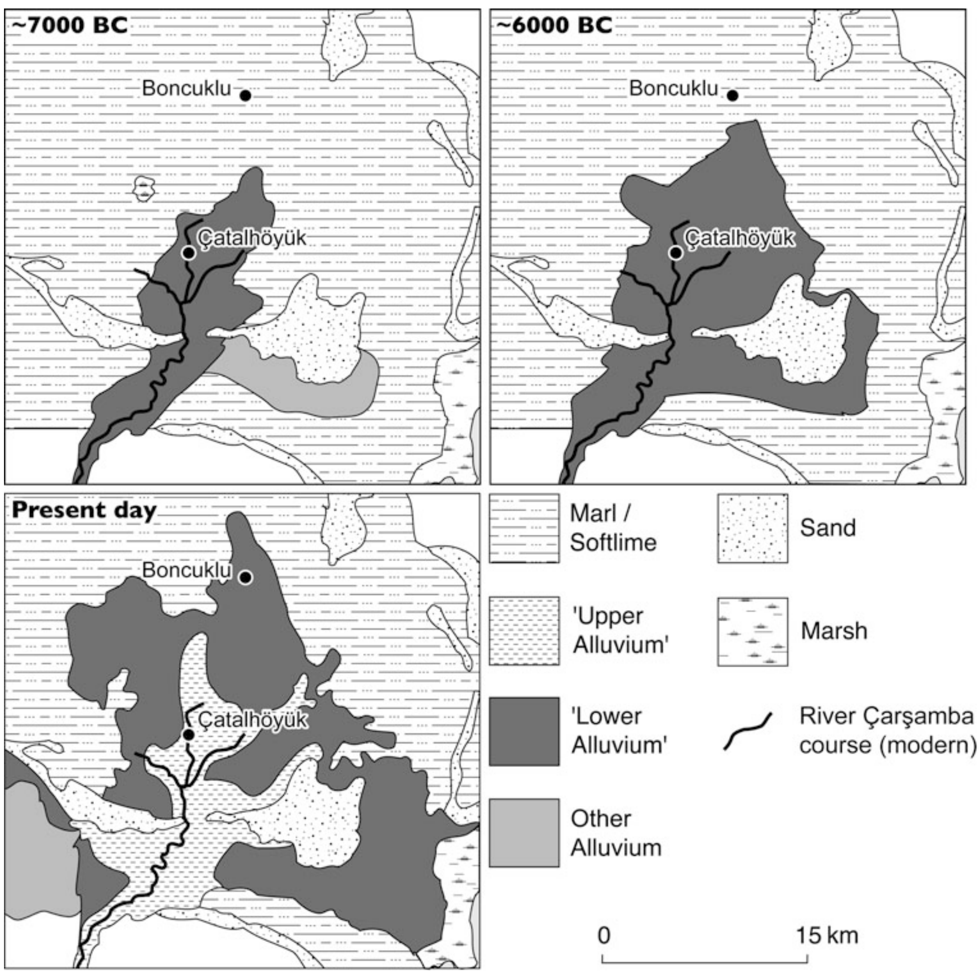
ÇATALHÖYÜK

Neil Roberts
School of Geography, Earth and Environmental Sciences, Faculty of Science and Environment, Plymouth University, Plymouth, Devon, UK

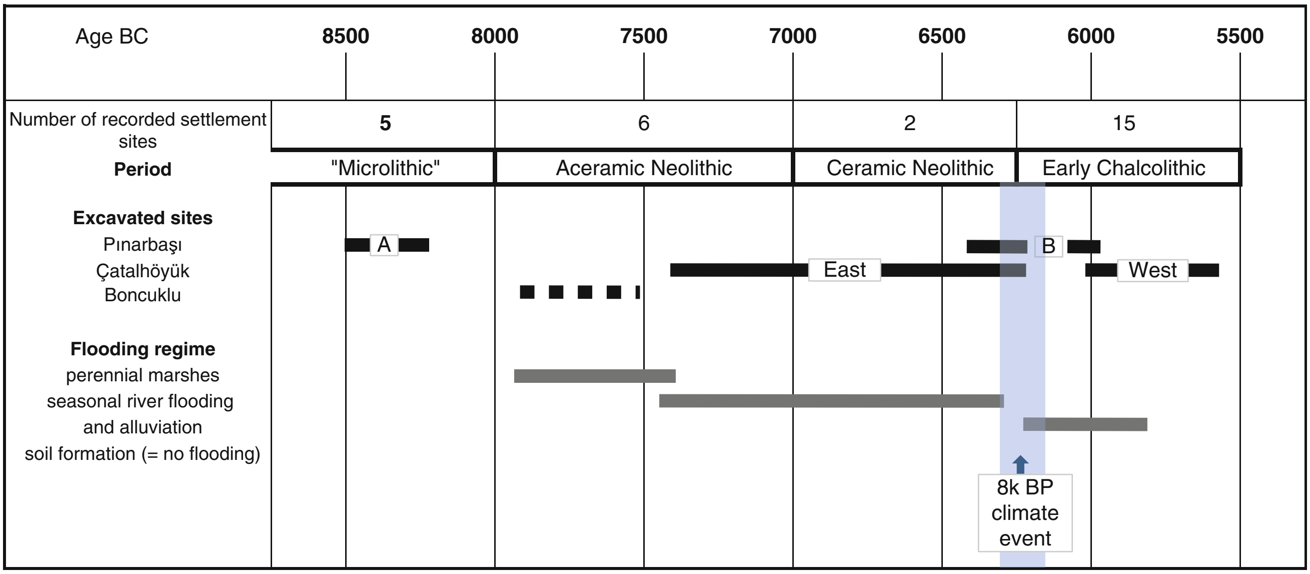
Çatalhöyük is a key Neolithic site located in south central Turkey. It is one of the largest and best studied early agricultural settlements in Southwest Asia, and it has also revealed a significant record of symbolic expression, such as wall paintings. Çatalhöyük, in fact, comprises two mounds, an East mound where most excavations have been focused and a smaller West mound of early Chalcolithic date. Çatalhöyük was originally excavated in the early 1960s by James Mellaart, but archaeological fieldwork subsequently stopped and recommenced only in 1993 under the overall direction of Ian Hodder – see Hodder (2006) for a summary.

Çatalhöyük is located on a gently sloping alluvial fan delta of the Çarşamba river, which has prograded across the bed of a large former lake that covered the Konya basin during the late Pleistocene (Figure 1). The plain lies at an elevation of ~1,000 m asl and lacks any surface outlet. Its climate is semiarid continental Mediterranean, in contrast to the surrounding well-watered mountain watershed. In contrast to initial speculations by Cohen (1970), studies by Roberts (1982) showed that (1) the main shrinkage of the Pleistocene Konya lake occurred prior to 16,000 BC, i.e., well before the first Neolithic occupation, and (2) significant post-occupation alluviation has occurred at Çatalhöyük. This continued deposition of alluvium means that modern soil type distributions (Driessen and de Meester, 1969) do not provide a reliable guide to those that existed around the site in prehistory. A comprehensive geoarchaeological field program took place between 1993 and 1999 linked to the current excavations at Çatalhöyük (Roberts et al., 1996; Roberts et al., 2007). This KOPAL (Konya basin Palaeoenvironment) project included vibrocoring, backhoe trenching, and study of off-site irrigation ditch sections, not only at Çatalhöyük but also at other archaeological sites located across the Çarşamba fan (Boyer et al., 2006).

Above pale gray marl deposited on the bed of the glacial-age lake, two principal alluvial units can be distinguished. A red-brown upper alluvial silt-clay dates from Bronze Age to post-Byzantine times. Beneath this lies a very dark gray lower alluvium comprising heavy, smectite-rich clay



Çatalhöyük, Figure 1 Maps showing the changing distribution of sediments around Çatalhöyük, near the start and end of the occupation of the East mound and at the present day (Modified from Boyer et al., 2006). At the microscale, this pattern would have been more spatially heterogeneous than shown here.



Çatalhöyük, Figure 2 Chronological chart showing recorded archaeological site numbers on or near the Çarşamba fan, individual site occupations, and changing flood regimes (From Roberts and Rosen, 2009).

that was laid down in a seasonally flooded backswamp environment. The top of the underlying marl is undulating due to Late Glacial eolian deflation, and as a result, the backswamp clay infill shows local-scale variations in thickness. Deposition of the backswamp clay at Çatalhöyük began ~7500 BC and ended by ~6000 BC with paleosol formation, and it coincides in time almost exactly with the Neolithic occupation (Figure 2). During the spring flood, much of the lower-lying land surrounding Neolithic Çatalhöyük would have been under water, which led Roberts and Rosen (2009) to propose that some cereal and pulse crops may have been grown on drier ground away from the alluvial fan.

In summer, the alluvial and marl plain dried out, and the Çarşamba river returned to its main channel, which ran next to Çatalhöyük. The strong wet-dry seasonal contrast in river and wetland hydrology has been confirmed by stable carbon and oxygen isotope analyses on samples taken across the surface of large *Unio* mollusk shells found on-site; the results for sequential samples showed isotopic variations explainable by seasonal fluctuations in local water levels as the bivalve's shell grew (Bar-Yosef Mayer et al., 2012). The river "flooding phase" at Çatalhöyük appears to have prompted a nucleated rather than dispersed settlement pattern on the Çarşamba fan, for only this single large site is known during the ceramic Neolithic, whereas several smaller settlements existed during both the preceding aceramic Neolithic and subsequent early Chalcolithic periods. The distinctive lifeways at Neolithic Çatalhöyük may, in consequence, have been partly an adaptation to specific hydro-environmental conditions.

The "flood phase" at Çatalhöyük can be linked to a period of wetter climate in the eastern Mediterranean during the early Holocene, and its ending coincides with the well-known 8.2 ka BP cold, dry climatic event. However, lake isotope data show that wetter climatic conditions in central Turkey had started by 9500 BC and continued until ~4500 BC, thus spanning a longer time period than the Çarşamba flood phase. Its timing must therefore have been affected by local factors, such as river avulsion and a changing depocenter, as well as regional climatic changes. Its onset, for example, would have been affected by a change in river course from an easterly to a northerly orientation when the Çarşamba broke through a sand spit of the former Konya lake (Figure 1).

More recent geoarchaeological fieldwork has been extended to include the nearby predecessor aceramic Neolithic site of Boncuklu, as well as further analysis of the sediment fill at and around Çatalhöyük, e.g., the sourcing of mudbricks and lime plasters (Love, 2012; Doherty, 2013). A new program of coring and ditch sectioning around the mounds took place in 2007–2009 in order to build a picture of the site environs at higher spatial resolution. At this fine spatial scale, the Neolithic landscape would have been a mosaic of upstanding marl hummocks, seasonally wet flood basins, and riparian zone river channels, some of which would have provided microhabitats suitable for more intensive "garden-scale" crop cultivation (Charles et al., 2014).

Çatalhöyük lies close to the volcanic terrain of Cappadocia, from where it obtained obsidian for lithic artifacts. A tephra layer found in eastern Mediterranean lake and marine cores has been linked geochemically to one of the Central Anatolian stratovolcanoes and dates to the ceramic Neolithic (Zanchetta et al., 2011; Schmitt et al., 2014). This may provide an explanation for an enigmatic wall painting at Çatalhöyük, which has been interpreted as showing a -twin-peaked volcano erupting above a settlement.

Bibliography

Bar-Yosef Mayer, D. E., Leng, M. J., Aldridge, D. C., Arrowsmith, C., Gümüş, B. A., and Sloane, H. J., 2012. Modern and early-middle Holocene shells of the freshwater mollusc *Unio*, from Çatalhöyük in the Konya Basin, Turkey: preliminary palaeoclimatic implications from molluscan isotope data. *Journal of Archaeological Science*, **39**(1), 76–83.

Boyer, P., Roberts, N., and Baird, D., 2006. Holocene environment and settlement on the Çarşamba alluvial fan, south-central Turkey: integrating geoarchaeology and archaeological field survey. *Geoarchaeology*, **21**(7), 675–698.

Charles, M., Doherty, C., Asouti, E., Bogaard, A., Henton, E., Larsen, C. S., Ruff, C. B., Ryan, P., Sadvari, J. W., and Twiss, K. C., 2014. Landscape and taskscape at Çatalhöyük: an integrated perspective. In Hodder, I. (ed.), *Integrating Çatalhöyük: Themes from the 2000–2008 Seasons*. Los Angeles: UCLA Cotsen Institute of Archaeology Press. Çatal Research Project 10. British Institute at Ankara Monograph 49. Monumenta Archaeologica 32, pp. 69–87.

Cohen, H. R., 1970. The palaeoecology of south central Anatolia at the end of the Pleistocene and the beginning of the Holocene. *Anatolian Studies*, **20**, 119–137.

Doherty, C., 2013. Sourcing Çatalhöyük's clays. In Hodder, I. (ed.), *Substantive Technologies at Çatalhöyük: Reports from the 2000–2008 Seasons*. Los Angeles: UCLA Cotsen Institute of Archaeology Press. Çatal Research Project 9. British Institute at Ankara Monograph 48. Monumenta Archaeologica 31, pp. 51–66.

Driessen, P. M., and De Meester, T., 1969. *Soils of the Çumra Area, Turkey*. Centre for Agricultural Publishing and Documentation Wageningen, Agricultural Research Report 720. Wageningen: Pudoc.

Hodder, I., 2006. *The Leopard's tale: revealing the mysteries of Çatalhöyük*. New York: Thames & Hudson.

Love, S., 2012. The geoarchaeology of mudbricks in architecture: a methodological study from Çatalhöyük, Turkey. *Geoarchaeology*, **27**(2), 140–156.

Roberts, N., 1982. A note on the geomorphological environment of Çatal Hüyük, Turkey. *Journal of Archaeological Science*, **9**(4), 341–348.

Roberts, N., and Rosen, A., 2009. Diversity and complexity in early farming communities of Southwest Asia: new insights into the economic and environmental basis of Neolithic Çatalhöyük. *Current Anthropology*, **50**(3), 393–402.

Roberts, N., Boyer, P., and Parish, R., 1996. Preliminary results of geoarchaeological investigations at Çatalhöyük. In Hodder, I. (ed.), *On the Surface: Çatalhöyük 1993–95*. Cambridge/London: McDonald Institute for Archaeological Research/British Institute of Archaeology at Ankara, pp. 19–40.

Roberts, N., Boyer, P., and Merrick, J., 2007. The KOPAL on-site and off-site excavations and sampling. In Hodder, I. (ed.), *Excavating Çatalhöyük: South, North and KOPAL Area Reports from the 1995–99 Seasons*. Cambridge/London: McDonald Institute for Archaeological Research/British Institute of Archaeology at Ankara. Çatalhöyük Research Project 3. British Institute at Ankara Monograph 37, pp. 553–572.

Schmitt, A. K., Danišík, M., Aydar, E., Şen, E., Ulusoy, İ., and Lovera, O. M., 2014. Identifying the volcanic eruption depicted in a Neolithic painting at Çatalhöyük, Central Anatolia, Turkey. *PloS One*, **9**(1), e84711, doi:10.1371/journal.pone.0084711.

Zanchetta, G., Sulpizio, R., Roberts, N., Cioni, R., Eastwood, W. J., Siani, G., Caron, B., Paterne, M., and Santacroce, R., 2011. Tephrostratigraphy, chronology and climatic events of the Mediterranean basin during the Holocene: an overview. *The Holocene*, **21**(1), 33–52.

CAVE SETTINGS

Panagiotis Karkanas[1] and Paul Goldberg[2]
[1]Ephoreia of Palaeoanthropology & Speleology of Southern Greece, Athens, Greece
[2]Department of Archaeology, Emeritus at Boston University, Boston, MA, USA

Definitions

Cave: natural cavity in a rock which is enterable by people.

Karst: a terrain that is formed principally by the solution of the rock.

Introduction

Caves constitute a disproportionately large part of the surviving archaeological record for many prehistoric periods (Straus, 1997). Their stability in the landscape attracted humans in search of shelter early in the history of humankind, and at the same time, they facilitated the accumulation of sediment and cultural material. The lengthy geologic and archaeological record that has built up within some caves provides the basic data of prehistoric archaeology in many regions of the world. Caves are also parts of drainage systems as well as ground water flow paths, making them important water sources that may partly explain their early use. It has been suggested that caves provide ready-made natural structures without the need of any significant adaptation of human behavior, and in this way, they were convenient and useful for a variety of purposes (Skeates, 1997; Straus, 1997). Caves are an example of bounded space, and like architectural forms, they can be carefully manipulated to create inhabitable, delineated areas where such spaces do not exist in nature (Kent, 1990). As such, caves provide not only natural shelter and protection but also a memorable and confined living space with a sense of durability and familiarity, probably precursors of the modern idea of "home." Caves, therefore, have been considered to be the first "home base" sites during the late Middle Pleistocene (Rolland, 2004).

Caves have varying and changing uses across different cultures. Early in the evolution of humans, they were the focus of hominin occupation. Examples include the famous caves within the Cradle of Humankind in South Africa, where important early hominin fossils have been found (e.g., Pickering and Kramers, 2010). However, it is believed that widespread, regular cave occupation did not begin before later Acheulian horizons, and not until the Middle Paleolithic are caves more systematically exploited. The use of fire made deep caves available for specialized ritual functions, as is indicated by the Upper Paleolithic art caves of France and Spain. Later, during the Neolithic, an expansion of cave use is observed, as groups exploited cave spaces as part of a pastoral economy (Tolan-Smith and Bonsall, 1997). In addition to

Cave Settings, Figure 1 Photograph of the area around Klissoura Cave 1 (*arrow*) showing the typically rugged Mediterranean karstic terrain developed in limestone.

dwellings, caves have also been employed as storage sites, cooking places, cemeteries, and temples.

Cave formation

Most caves develop in limestone and similar carbonate rocks. Their formation is related to karst processes with the solution of rocks by meteoric (phreatic) water (Figure 1). Atmospheric carbon dioxide (CO_2) dissolved in rainwater becomes acidic and, as a consequence, is capable of dissolving carbonate rocks. Rainwater entering at the ground surface may be further enriched with CO_2 derived from decayed vegetal matter and fauna from the soil. Dissolution of carbonate rocks may follow changes in lithology, such as contacts between pure and impurelimestones and limestones and other non-carbonate rocks (including shales or various igneous rocks).

Water circulation is also greater near joints, bedding planes, and faults. Therefore, in the early stages of their formation, caves act as water conduits. When water-filled passages drain, hydrostatic support stops and breakdown commences. In any cave evolution sequence, the spalling of wall and ceiling surfaces is an inevitable phase that leads to partial or complete infilling but also to enlarging and generally changing the configuration of the cave (Gillieson, 1996). Other mechanisms of cave development in carbonate rocks include dissolution by sulfuric acid produced from upwelling thermal waters that oxidize sulfides present in the limestone or from oxidized hydrogen sulfide emanating from deep hydrocarbon sources. Sulfur-oxidizing and sulfur-reducing bacteria are involved in this type of speleogenesis (White, 2000).

Caves may occur in sandstones and quartzites, evaporates (e.g., gypsum), igneous rocks such as basalts and granites, as well as in ice. In some of these cases, dissolution is also the major factor of cave formation, particularly in sandstones and evaporitic rocks. In sandstones, if the cementing material is carbonate, then cave formation will proceed according to the karstification process described above. In quartzites and sandstones, silica cement dissolution is very slow, and mechanical removal of loosened grains by fast moving groundwater is an additional process leading to enlargement (Martini, 2000). Caves in basalt are often lava caves formed by the draining of lava tube feeding networks during the eruption period.

Along karstic coastal areas, caves develop where marine and fresh water meets (Mylroie and Carew, 2000). These shallow water occurrences are based on the same principle observed for the formation of deepwater karstic environments, where additional dissolution is achieved by mixing waters saturated with different amounts of carbon dioxide. Sea caves are formed by wave erosion during prolonged sea-level stands (Figure 2). They can develop in any kind of rock by mechanical weakening along rock discontinuities and the chemical action of saltwater (Mylroie, 2005). Sea caves can provide

Cave Settings, Figure 2 Photograph of two sea caves on the southern coast of South Africa, near Die Kelders Cave. Note the remnants of bedded aeolianites at the top (*arrow*) once covering and blocking the entrance to the caves.

useful information on the past sea-level fluctuations in relation to human occupation (e.g., Goldberg, 2000; Kuhn et al., 2009; Karkanas and Goldberg, 2010). Windblown sand can also scour relatively soft rocks and form aeolian caves of appreciable size (White and Culver, 2005).

Detailed study of the formation of caves, as well as their history prior to human occupation, is normally not undertaken in archaeological projects. Yet, such studies contribute significantly to our understanding of the paleoenvironment and evolution of the landscape, and they can reveal potential links to the eventual presence of humans. In addition, the processes responsible for a cave's formation are often ongoing, albeit at a slower rate, throughout its entire history, and consequently they affect or determine the type of deposits, structure, and location. For example, Qesem Cave in Israel was formed by a combination of processes that include subsidence and sagging of the bedrock into deeper voids formed by deep-seated dissolution (Frumkin et al., 2009). The gradual sagging of the basal bedrock layers also affected the overlying sediments such that the cemented parts of the cave deposits (indurated through hardening of the matrix) have fractured along the walls allowing the central area to sink through gravitational slumping. These processes have resulted in hanging ledges of cemented deposits clinging to the cave walls while the adjacent sunken area in the center subsequently filled in. Then everything was covered with new collapse material. Both the complex stratigraphy and the sedimentary character of the cave are better explained when the processes responsible for cave formation are clearly understood (Karkanas et al., 2007).

Cave sediments

Caves are often perfect sedimentary traps, accumulating and protecting the stratigraphic record from many postdepositional subaerial processes. Cave sedimentary facies are quite useful in interpreting and reconstructing depositional histories, which can track changes in earth system processes (Springer, 2012), thereby yielding insights into climate and landscape evolution within the area (Goldberg, 2000; Pickering et al., 2007; Karkanas et al., 2008; Kourampas et al. 2009). Sediments from different sources accumulate within caves, and thus complex stratigraphic sequences may result. At the same time, however, such instances provide some of the best cases for studying past human behavior (Macphail et al., 1997; Karkanas et al., 2007; Meignen et al., 2007; Goldberg et al., 2009).

Geogenic sediments

Caves are repositories of primary and secondary clastic sediments, but they also contain primary and secondary chemical sediments. Primary clastic sediments are derived from breakdown of the walls and ceiling of the cave (known as autochthonous or endogenous sediment). Cave mouths are more sensitive to surface weathering conditions, and, therefore, they can be dominated by processes not normally encountered in deeper passages. Since

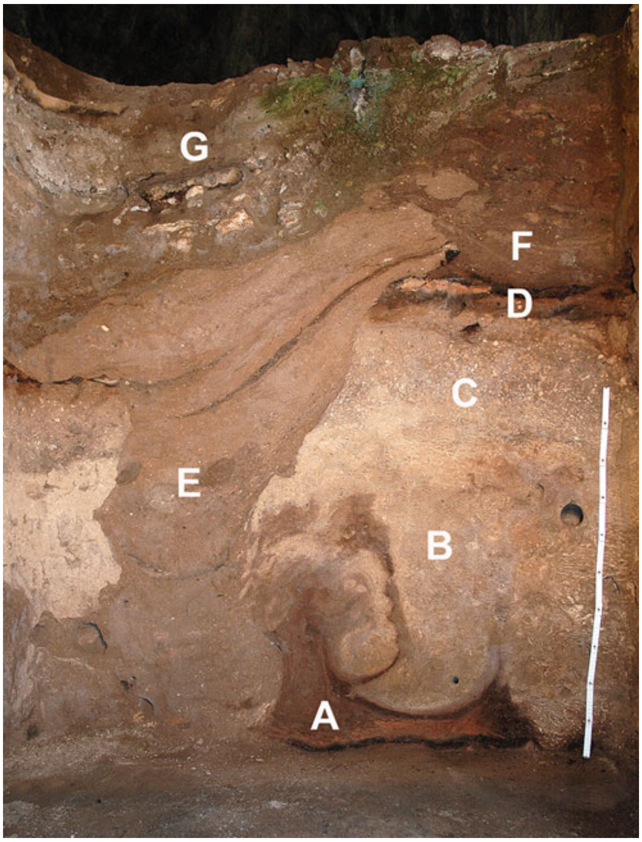
Cave Settings, Figure 3 Pile of breakdown material capped by brown infiltrated clay coming down a fracture in the bedrock (*arrow*). Unnamed cave in Israel, near Qesem Cave.

human occupation is typically restricted to the entrance area of caves (particularly the deeper ones), these entrance facies are most important from a geoarchaeological perspective. Breakdown is extremely common at the entrance area, and roof collapse produces talus cones marking the gradual retreat of the cave (Goldberg et al., 2007) (Figure 3). Therefore, slope processes often dominate the entrance area of caves occupied by humans (Karkanas et al., 2008). Frost action is also observed only in the entrance area of a cave. Cryoclastic sediments, the famous *éboulis* of the French literature, constitute a significant part of the sediments in present-day temperate environments. However, similar angular coarse particles can be produced by a variety of processes including hydration shuttering and seismic activity (for a review, see Woodward and Goldberg, 2001).

Secondary clastic sediments from the outside (allochthonous or exogenous) enter the cave through a variety of processes, such as fluvial deposition, aeolian activity, and mass movement (debris and mudflows, creep, falls, slumps, etc.). The main sources of this sediment are sinking streams carrying sediments from nearby drainage basins, soils, and weathering residuum from the ground surface that are flushed into caves through sinkholes and open fractures by storm runoff and sediment influxes from overlying rock formations through open fractures (Bosch and White, 2004).

Sediments deposited from high-energy water flow are not frequently encountered in archaeological cave sequences. However, fluvially transported endokarstic (subsurface) gravels often associated with bedded sands and silts have been reported in some archaeological caves (Macphail and Goldberg, 2003; Braillard et al., 2004). In some cases, invasive waters may enter caves through the karstic system, producing complex erosional features including irregular channels and underground tunnels (Karkanas, 2001). This often leads to a very complicated stratigraphy with several phases of sedimentation and erosion (Figure 4).

Low-energy water flow may transport material from outside and redistribute it toward the back of caves. Finely laminated, moderately sorted, fine-grained sediments deposited by sheetflow are frequently encountered in the entrance area (Karkanas, 2001; Goldberg et al., 2007). Debris flow and other types of deposit produced by mass movement are probably the most widespread sediments observed in archaeological sequences within caves. They appear in the form of sloping beds of angular to subrounded gravel, floating in unsorted fine-grained matrix. Gravel clustering, floating boulders, coarse "tails," and imbrication (overlapping) of coarser particles are indications of sediment gravity flows (Figure 5). They are formed when colluvium that has accumulated in the entrance is destabilized by water saturation and fails under the force of gravity (Karkanas et al., 2008; Mallol et al., 2009). Water saturation can also destabilize previously deposited sediments with substantial anthropogenic materials and redistribute them by the force of gravity, producing slumping and debris flows (Figure 4) (Karkanas and Goldberg, 2010). In cold climates, solifluction deposits



Cave Settings, Figure 4 Photograph of complex stratigraphy at Theopetra Cave, Greece. The lower sedimentary sequence, comprising cryoturbated burnt features (*A*) and in situ burnt remains (*D*), is truncated by a channel formed by invasive waters that was later filled with sediment (*E*). Slumping has reworked part of the fill, shown by whole pieces of the channel fill (*F*), and finally the sequence was capped by reworked burnt stabling remains (*G*).

occur widely in caves, where they are characterized by rounded aggregates and mineral grains coated by microlaminated silts due to the rotation they undergo during displacement (Goldberg 1979a; Courty and Vallverdú, 2001; Karkanas et al., 2008). Orientation of clasts provides useful information about the type and direction of flow (e.g., Bertran and Texier, 1999; Lenoble et al., 2008).

Another fine-grained sediment frequently observed in archaeological caves is infiltrated fine-grained sediment and soil flushed through joints, fractures, and generally thin discontinuities of the bedrock (Figure 3). This sediment is often deposited as hyperconcentrated slurries and mudflows producing cones where they exit from the joints. More diluted flows can slowly percolate inside coarser roofspall and accumulate within the voids, thereby creating secondary-filled, matrix-supported angular gravels. Piles of coarse breakdown deposits can be further redistributed by gravity when lubricated by infiltrated clay slurries (Karkanas et al., 2007).

In coastal areas, aeolian deposition is widespread. Several important sites along the coast of South Africa and the Mediterranean are dominated by windblown deposits of well-sorted sand interfingered with anthropogenic sediments (Figure 2) (Goldberg, 1973, Deacon and Geleijnse, 1988; Tsatskin et al., 1995; Goldberg 2000; Macphail and Goldberg, 2000; Jacobs et al., 2006; Karkanas and Goldberg, 2010). Aeolian silt (dust) is also an important component of cave sediments – particularly in the circum-Mediterranean zone – but due to its slow accumulation rate, it is often intermixed with coarser roofspall, aeolian sand, and other clastic or anthropogenic components, such as the similar-sized wood ash. These mixtures make the interpretation of such sediments very difficult in the field. In Dust Cave, Alabama, USA, original aeolian silts occur as rounded soil aggregates and are incorporated within the coarser deposits. Here, dust originated in the nearby floodplain of the Tennessee River and along the limestone bluffs above the cave, and it was transported directly and indirectly into the cave by different mechanisms (Sherwood et al., 2004; Goldberg and Sherwood, 2006). In general, aeolian deposits are quite loose and easily disturbed by secondary sedimentary processes. Water seeping from fractures in cave walls or flushed through conduits can redistribute aeolian sediment and produce finely laminated deposits (Goldberg, 2000).

Primary chemical sediments are mainly in the form of speleothems (stalagmites, stalactites, flowstones, etc.). They are deposited by carbonate-saturated dripping, seeping, or flowing waters on the surface of the caves. These sediments are suitable for high-resolution dating such as uranium-series techniques, and when intercalated with clastic sediments, they can provide secure stratigraphic and chronostratigraphic markers (Moriarty et al., 2000; Pickering et al., 2007).

Primary biogenic sediments are mainly represented by the accumulation of large amounts of bat guano but also excrements from other animals that occupy cave interiors (bears, hyenas, etc.). The decay of biogenic sediments leads to chemical alteration of all previously deposited sediments and the formation of a suite of authigenic phosphate minerals (Karkanas et al., 2000; Shahack-Gross et al., 2004). Diagenesis is often very aggressive in caves because they also contain an active and confined hydrologic regime (for the details of these diagenetic processes, see the entry on "Chemical Alteration"). As several studies in the Near East and Europe have shown, phosphate diagenesis can have a dramatic effect upon the preservation of archaeological materials, leading to complete dissolution of bones and all kinds of calcareous materials such as ash, shells, and limestone particles (Goldberg and Nathan, 1975; Weiner and Bar-Yosef, 1990; Weiner et al., 1993; Schiegl et al., 1996; Karkanas et al., 1999; Karkanas et al., 2000; Karkanas et al., 2002; Weiner et al., 2002).

Cave Settings, Figure 5 Debris flow deposits showing alternating finer and coarser debris sloping downward to the right. Also seen are floating boulders within a fine clayey matrix as well as clustering and imbrication of coarser clasts at Dadong Cave, China.

Anthropogenic sediments

Human activity in caves produces a variety of sediments, but burnt remains are often volumetrically the most significant. These deposits include ash, charcoal, and deposited sediments that were previously heated (see the entry on "Hearths and Combustion Features" for details). The use of fire in prehistoric times is of great interest because it is one the most important elements of human evolution (Rolland, 2004). Since burning produces abundant sediment in the form of calcitic wood ash and charred remains (Courty et al., 1989), such residues are generally preserved in the calcareous environments of limestone caves (Figure 6), and their volume, constituents, microstructure, geometry, and pattern can provide evidence relating to the intensity of occupation and organization of activities (e.g., Meignen et al., 2007). Note that the general structure of burnt remains survives even after severe phosphate alteration (Schiegl et al., 1996; Karkanas, 2001; Goldberg et al., 2007).

Although the hypothesis has been proposed only recently, it has been recognized that large amounts of organic matter were often introduced into some Stone Age caves by humans for subsistence and bedding (Figure 7), offering new dimensions for analysis and a more profound understanding of the behavioral complexity of humans (Goldberg et al., 2009; Cabanes et al., 2010; Wadley et al., 2011). Later, stabling activities in caves from the Neolithic onward deposited large quantities of dung. Studies on the composition, macro-, and microstructure of stable remains and their spatial organization have contributed to an improved understanding of the new economic conditions introduced with the advent of animal domestication (Courty et al., 1991; Macphail et al., 1997; Boschian and Montagnari-Kokelj, 2000; Karkanas, 2006) (see the entry on "Pastoral Sites" for more details).

Transported and introduced natural clastic sediments are also encountered in cave sequences. In several cases, prehistoric constructions such as clay hearths and platforms have been identified, representing outside materials accumulated and shaped into man-made structures (Karkanas et al., 2004; Goldberg and Sherwood, 2006). Nonetheless, one of the most important but also neglected aspects of human-induced sedimentary processes is the redistribution and general (often penecontemporaneous) reworking of previously deposited geogenic or anthropogenic sediments by human activities. The digging of pits, dumping of burnt remains and food refuse, sweeping or shoveling out of stable residues, and trampling are among the most common secondary anthropogenic processes that rearrange sediment (Goldberg and Sherwood, 2006). Since these processes alter primary sedimentary structures and tend to mix contents and textures, they are generally difficult to discern and interpret by eye in the field. These effects can be studied with the proper analytical tools, and the results of such examinations can considerably enhance our knowledge of human behavior.

Cave Settings, Figure 6 Stratigraphic section of overlapping, mostly in situ hearth structures from the Middle Paleolithic sequence at Theopetra Cave, Greece. Note the circular burrow perforating the upper hearth complex in the center of the photo.

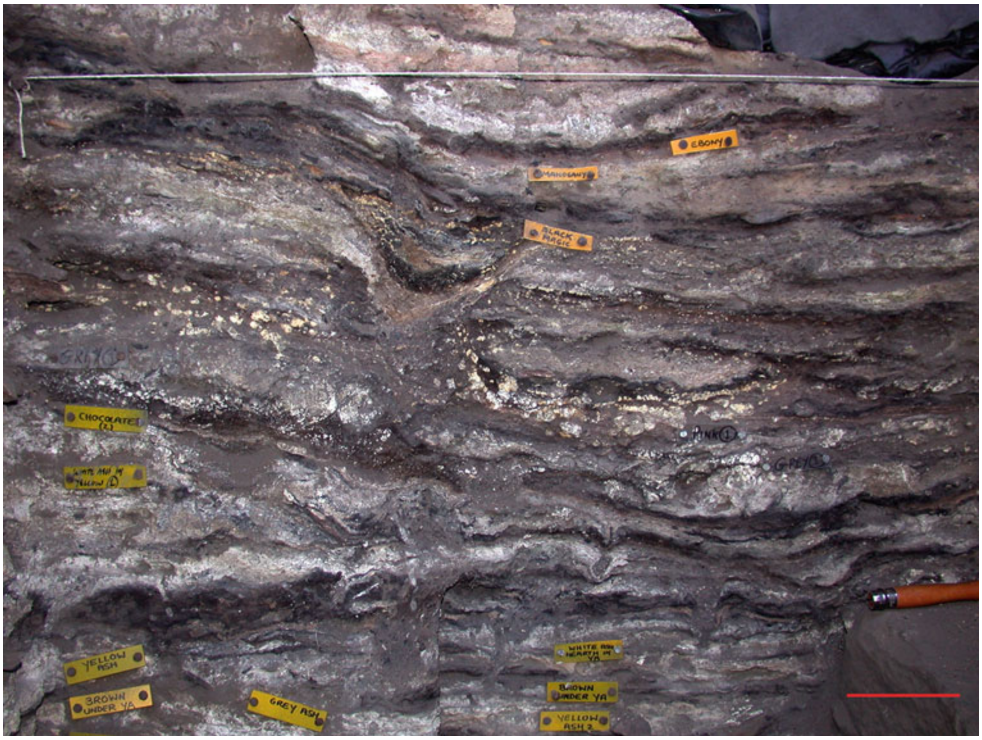
Methods of study

Caves were one of the first environments in which sedimentological techniques, such as grain-sized analysis, particle shape and composition, pH, and calcium carbonate and organic matter content, were applied to the study of archaeological deposits in order to interpret the depositional history of cave sediments (Bordes, 1972; Laville et al., 1980; Farrand, 2000). Although these data can provide useful quantitative information in some cases, they have mostly failed to (1) identify important anthropogenic components, such as calcareous ash, and (2) disentangle the complex syndepositional and postdepositional processes related to geogenic, biogenic, and anthropogenic activities. Indeed, as early as the 1970s, it was realized that classical sedimentological analyses did not reveal important postdepositional processes that constitute the basis of paleoclimatic interpretations (Goldberg, 1979a). Archaeological cave sediments were also the first to be studied by micromorphology, the study of intact sediments and soils under the microscope (Goldberg, 1979a; Goldberg, 1979b; Courty et al., 1989). Micromorphology is the best technique for unraveling such complex processes, and it provides the initial and basic framework for applying other techniques that can further elucidate details of both sedimentary accumulation and diagenetic changes. High-resolution approaches such as SEM, EDAX, XRD, and FTIR have been employed in the study of archaeological cave sediments along with micromorphology (Goldberg and Nathan, 1975; Bull and Goldberg, 1985; Weiner et al., 1993; Schiegl et al., 1996; Karkanas et al., 1999).

Cave sediments and environmental change

The usefulness of caves as archives of environmental change is controlled by the temporal resolution of the sedimentary record and the environmental sensitivity of the cave (Woodward and Goldberg, 2001). Studying caves as parts of the regional geomorphic system enables inferences relating to climatic and other changes in the regime of landscape processes for the entire area (Gillieson, 1996). There are, however, some limitations when trying to reconstruct paleoclimate using cave sediments. First, local factors govern the microclimate of the cave and may play a significant role in the way internal sedimentation occurs. Caves are complex settings with a unique microenvironment that is influenced by bedrock lithology, elevation, aspect, local drainage, internal configuration, and human activity (Goldberg and Sherwood, 2006). Second, caves are parts of larger karstic systems where sediments are circulating and stored for considerable periods of time before ultimately being deposited within the cave under study. This lag effect hampers easy interpretations based on weathering indices of external soil sources of the surrounding area. Fortunately in many regions, caves preserve distinct suites of sedimentary features that can provide the best available terrestrial record when combined with detailed stratigraphic analysis and comprehensive field observations, then corroborated by instrumental laboratory analysis.

The earliest micromorphological studies conducted on cave sediments in the Dordogne region of France clearly demonstrated episodes of colluviation, flowstone, and



Cave Settings, Figure 7 Field view of the profile along B4/B5 at Sibudu Cave, South Africa, showing the superposition of numerous combustion features. Whereas these features appear similar in the field, in thin section, cm-thick differences in composition can be observed, reflecting different materials (e.g., sedge phytolith remains of bedding) and activities (e.g., burning and trampling) (see Goldberg et al., 2009; Wadley et al., 2011). Scale bar = 10 cm.

stalactite formation, alternating with ice lensing and cryoclastism (Goldberg, 1979a; Courty, 1989). Frost-related processes affecting fine-grained sediments, such as cryoturbation and ice lensing, are particularly informative about climatic changes in caves (van Vliet-Lanoë, 1985) (Figure 4). Clastic deposits showing evidence of frost action may alternate with non-affected sediment or flowstones, which generally form during warmer climatic conditions. However, even in these cases, prior to a final interpretation, other environmental indices should be considered, such as phytoliths, charcoal, and macrobotanical remains, along with a thorough micromorphological analysis of the deposits. For example, flowstones intercalating with frost-affected sediments would be typically considered to be an indicator of warmer climate intervals. However, there are cases where flowstones can also be deposited under cold climate regimes (Bar-Matthews and Ayalon, 2011), and they themselves can also be affected by frost action (Courty et al., 1989; Karkanas et al., 2008). It should be remembered that sediments affected by frost action may have been deposited already and were not necessarily formed during a cold climate. In the end, it is the association and spatial distribution of all sedimentary features, both primary deposits and secondary disturbances, that ultimately lead to a thorough understanding of the sedimentary processes and stratigraphy of a cave site.

Finally, recent advances in dating techniques and isotopic analyses have made speleothem records the key proxy in reconstructing paleoclimatic change (e.g., Cheng et al., 2009). Highly detailed analysis of speleothem laminae can produce a yearly or even seasonal climatic record, and these complete climatic records can be compared to the archaeological record. Important inferences about cultural transitions, social changes, and even the collapse of civilizations (Bar-Matthews and Ayalon, 2011) can be made, though the exact role played by these detailed climatic changes in influencing human behavior must still be demonstrated with further evidence.

Cave sediments and human behavior

As mentioned above, the use of fire is of major importance to understanding human behavior in prehistory. Claims for early control of fire have been challenged by studies of cave sediments using micromorphology and FTIR. In Zhoukoudian, China, the purported burnt features were found to consist of dark brown and reddish-brown, finely laminated silts and clays interbedded with decayed fragments of organic matter. The sediments were therefore not the result of in situ burning as was previously interpreted based on field observations, but they were instead deposited in standing or slow-flowing water

(Goldberg et al., 2001). In contrast, the Middle Pleistocene cave of Qesem, Israel, contains sediments that appear in the field as a light reddish-brown, strongly lithified, and mostly massive deposit that archaeologists recognize as a common fill of angular rock fragments and matrix called "cave breccia." Based on micromorphological observations as well as mineralogical and isotopic analysis, however, it was discovered that a considerable part of these sediments in fact consist of recrystallized wood ash, indicating the presence of fire in antiquity (Karkanas et al., 2007).

In caves, combustion features can be well preserved, thus offering a clear picture of the burning activities related to them. In Kebara Cave, Israel, field observations and micromorphology revealed a variety of features including massive accumulations and small patches of charcoal and ashes, intact hearth structures, and diffuse ashy lenses. The geometry, composition, and microstructure of each of these types of deposits provided information on specific fire-related activities and events such as dumping, trampling, and cleaning that can place other archaeological materials into the context of a living settlement (Goldberg et al., 2007; Meignen et al., 2007).

In Dust Cave, Alabama, USA, prepared thin clay constructions were identified within Paleo-Indian strata based on field and micromorphological observations. As these features preserved intact lenses of ash, they provided data on fuel, feature type, and function. It was thus suggested that these flat clay structures were used as special heated cooking surfaces for roasting or specialized food processing (Sherwood and Chapman, 2005). Similar structures have been also identified in the Aurignacian sequence of Klissoura Cave 1, Greece. Here, micromorphology corroborated by FTIR and differential thermal analyses (DTA) revealed that the clay structures were heated in place at relatively low temperatures (400–600 °C), implying that they were also used as hearths for special cooking activities (Karkanas et al., 2004).

Study of cave sediments from later periods has offered insights into questions related to the nature of cave occupation, their monofunctional or polyfunctional uses, differences in the exploitation of site space, and the seasonality of occupation (Courty et al., 1991; Boschian and Montagnari-Kokelj, 2000; Angelucci et al., 2009). Several studies have shown that that during the Neolithic, caves were used both for herbivore stabling and for domestic occupation and that different areas within the caves were used for each purpose (Macphail et al., 1997; Karkanas, 2006).

Summary

Caves occupy an important place in archaeology and environmental studies. As unique landforms within the earth, they act as sediment repositories preserving detailed records of human activities and paleoenvironmental changes. Sedimentary sequences within caves comprise not only a suite of primary and secondary clastic sediments but also primary chemical and biogenic sediments, as well as secondary alteration deposits. Human activities add to the complexity of the sedimentary processes by adding organic-rich deposits, combustion features, and the reworking of previously deposited sediments. Despite these complications, detailed sedimentological studies at the microscopic scale supplemented by high-resolution instrumental techniques can untangle these complex processes, offering some of the best opportunities to study early human behavior.

Bibliography

Angelucci, D. E., Boschian, G., Fontanals, M., Pedrotti, A., and Vergès, J. M., 2009. Shepherds and karst: the use of caves and rock-shelters in the Mediterranean region during the Neolithic. *World Archaeology*, **41**(2), 191–214.

Bar-Matthews, M., and Ayalon, A., 2011. Mid-Holocene climate variations revealed by high-resolution speleothem records from Soreq Cave, Israel and their correlation with cultural changes. *The Holocene*, **21**(1), 163–171.

Bertran, P., and Texier, J.-P., 1999. Facies and microfacies of slope deposits. *Catena*, **35**(2–4), 99–121.

Bordes, F., 1972. *A Tale of Two Caves*. New York: Harper and Row.

Bosch, R. F., and White, W. B., 2004. Lithofacies and transport of clastic sediments in karstic aquifers. In Sasowsky, I. D., and Mylroie, J. (eds.), *Studies of Cave Sediments. Physical and Chemical Records of Paleoclimate*. New York: Kluwer Academic/Plenum Publishers, pp. 1–22.

Boschian, G., and Montagnari-Kokelj, E., 2000. Prehistoric shepherds and caves in the Trieste karst (northeastern Italy). *Geoarchaeology*, **15**(4), 331–371.

Braillard, L., Guélat, M., and Rentzel, P., 2004. Effects of bears on rockshelter sediments at Tanay Sur-les-Creux, southwestern Switzerland. *Geoarchaeology*, **19**(4), 343–367.

Bull, P. A., and Goldberg, P., 1985. Scanning electron microscope analysis of sediments from Tabun Cave, Mount Carmel, Israel. *Journal of Archaeological Science*, **12**(3), 177–185.

Cabanes, D., Mallol, C., Expósito, I., and Baena, J., 2010. Phytolith evidence for hearths and beds in the late Mousterian occupations of Esquilleu cave (Cantabria, Spain). *Journal of Archaeological Science*, **37**(11), 2947–2957.

Cheng, H., Edwards, R. L., Broecker, W. S., Denton, G. H., Kong, X., Wang, Y., Zhang, R., and Wang, X., 2009. Ice Age terminations. *Science*, **326**(5950), 248–252.

Courty, M.-A., 1989. Analyse microscopic des sédiments du remplissage de la grotte de Vaufrey (Dordogne). In Rigaud, J.-P. (ed.), *La Grotte Vaufrey à Cenac-et-Saint Julien (Dordogne): Paleoenvironments, chronologie et activités humaines*. Paris: Ministère de la culture et de la communication & CNRS. Mémoires de la Societé préhistorique française, Vol. 19, pp. 183–209.

Courty, M.-A., and Vallverdú, J., 2001. The microstratigraphic record of abrupt climate changes in cave sediments of the western Mediterranean. *Geoarchaeology*, **16**(5), 467–499.

Courty, M.-A., Goldberg, P., and Macphail, R. I., 1989. *Soils and Micromorphology in Archaeology*. Cambridge: Cambridge University Press.

Courty, M.-A., Macphail, R. I., and Wattez, J., 1991. Soil micromorphological indicators of pastoralism; with special reference to Arene Candide, Finale Ligure, Italy. *Rivista di Studi Liguri*, **57**, 127–150.

Deacon, H. J., and Geleijnse, V. B., 1988. The stratigraphy and sedimentology of the main site sequence, Klasies River, South Africa. *South African Archaeological Bulletin*, **43**(147), 5–14.

Farrand, W. R., 2000. *Depositional History of Franchthi Cave. Sediments, Stratigraphy, and Chronology*. Bloomington/Indianapolis: Indiana University Press. Excavations at Franchthi Cave, Fascicle, Vol. 12.

Frumkin, A., Karkanas, P., Bar-Matthews, M., Barkai, R., Gopher, A., Shahack-Gross, R., and Vaks, A., 2009. Gravitational deformations and fillings of aging caves: the example of Qesem karst system, Israel. *Geomorphology*, **106**(1–2), 154–164.

Gillieson, D. S., 1996. *Caves: Processes, Development, Management*. Oxford: Blackwell.

Goldberg, P., 1973. *Sedimentology, Stratigraphy and Paleoclimatology of et-Tabun Cave, Mount Carmel, Israel*. PhD Dissertation, Dept. of Geological Sciences, University of Michigan, Ann Arbor.

Goldberg, P., 1979a. Micromorphology of Pech-de-l'Aze II sediments. *Journal of Archaeological Science*, **6**(1), 17–47.

Goldberg, P., 1979b. Micromorphology of sediments from Hayonim Cave, Israel. *Catena*, **6**(2), 167–181.

Goldberg, P., 2000. Micromorphology and site formation at Die Kelders Cave I, South Africa. *Journal of Human Evolution*, **38**(1), 43–90.

Goldberg, P., and Nathan, Y., 1975. The phosphate mineralogy of et-Tabun cave, Mount Carmel, Israel. *Mineralogical Magazine*, **40**, 253–258.

Goldberg, P., and Sherwood, S. C., 2006. Deciphering human prehistory through the geoarchaeological study of cave sediments. *Evolutionary Anthropology*, **15**(1), 20–36.

Goldberg, P., Weiner, S., Bar-Yosef, O., Xu, Q., and Liu, J., 2001. Site formation processes at Zhoukoudian, China. *Journal of Human Evolution*, **41**(5), 483–530.

Goldberg, P., Laville, H., and Meignen, L., 2007. Stratigraphy and geoarchaeological history of Kebara Cave, Mount Carmel. In Bar-Yosef, O., and Meignen, L. (eds.), *Kebara Cave, Part 1*. Cambridge: Peabody Museum of Archaeology and Ethnology, Harvard University, pp. 49–89.

Goldberg, P., Miller, C. E., Schiegl, S., Ligouis, B., Berna, F., Conard, N. J., and Wadley, L., 2009. Bedding, hearths, and site maintenance in the Middle Stone Age of Sibudu Cave, KwaZulu-Natal, South Africa. *Archaeological and Anthropological Science*, **1**(2), 95–122.

Jacobs, Z., Duller, G. A. T., Wintle, A. G., and Henshilwood, C. S., 2006. Extending the chronology of deposits at Blombos Cave, South Africa, back to 140 ka using optical dating of single and multiple grains of quartz. *Journal of Human Evolution*, **51**(3), 255–273.

Karkanas, P., 2001. Site formation processes in Theopetra Cave: a record of climatic change during the Late Pleistocene and early Holocene in Thessaly, Greece. *Geoarchaeology*, **16**(4), 373–399.

Karkanas, P., 2006. Late Neolithic household activities in marginal areas: the micromorphological evidence from the Kouveleiki caves, Peloponnese, Greece. *Journal of Archaeological Science*, **33**(11), 1628–1641.

Karkanas, P., and Goldberg, P., 2010. Site formation processes at Pinnacle Point Cave 13B (Mossel Bay, Western Cape Province, South Africa): resolving stratigraphic and depositional complexities with micromorphology. *Journal of Human Evolution*, **59** (3–4), 256–273.

Karkanas, P., Kyparissi-Apostolika, N., Bar-Yosef, O., and Weiner, S., 1999. Mineral assemblages in Theopetra, Greece: a framework for understanding diagenesis in a prehistoric cave. *Journal of Archaeological Science*, **26**(9), 1171–1180.

Karkanas, P., Bar-Yosef, O., Goldberg, P., and Weiner, S., 2000. Diagenesis in prehistoric caves: the use of minerals that form in situ to assess the completeness of the archaeological record. *Journal of Archaeological Science*, **27**(10), 915–929.

Karkanas, P., Rigaud, J.-P., Simek, J. F., Albert, R. M., and Weiner, S., 2002. Ash, bones and guano: a study of the minerals and phytoliths in the sediments of Grotte XVI, Dordogne, France. *Journal of Archaeological Science*, **29**(7), 721–732.

Karkanas, P., Koumouzelis, M., Kozlowski, J. K., Sitlivy, V., Sobczyk, K., Berna, F., and Weiner, S., 2004. The earliest evidence for clay hearths: Aurignacian features in Klisoura Cave 1, southern Greece. *Antiquity*, **78**(301), 513–525.

Karkanas, P., Shahack-Gross, R., Ayalon, A., Bar-Matthews, M., Barkai, R., Frumkin, A., Gopher, A., and Stiner, M. C., 2007. Evidence for habitual use of fire at the end of the Lower Paleolithic: site-formation processes at Qesem Cave, Israel. *Journal of Human Evolution*, **53**(2), 197–212.

Karkanas, P., Schepartz, L. A., Miller-Antonio, S., Wei, W., and Weiwen, H., 2008. Late Middle Pleistocene climate in southwestern China: inferences from the stratigraphic record of Panxian Dadong Cave, Guizhou. *Quaternary Science Reviews*, **27**(15–16), 1555–1570.

Kent, S., 1990. Activity areas and architecture: an interdisciplinary view of the relationship between use of space and domestic environments. In Kent, S. (ed.), *Domestic Architecture and the Use of Space*. Cambridge: Cambridge University Press, pp. 1–8.

Kourampas, N., Simpson, I. A., Perera, N., Deraniyagala, S. U., and Wijeyapala, W. H., 2009. Rockshelter sedimentation in a dynamic tropical landscape: Late Pleistocene-Early Holocene archaeological deposits in Kitulgala Beli-Lena, southwestern Sri Lanka. *Geoarchaeology*, **24**(6), 677–714.

Kuhn, S. L., Stiner, M. C., Güleç, E., Özer, I., Yılmaz, H., Baykara, I., Açıkkol, A., Goldberg, P., Molina, K. M., Ünay, E., and Suata-Alpaslan, F., 2009. The early Upper Paleolithic occupations at Üçağızlı Cave (Hatay, Turkey). *Journal of Human Evolution*, **56**(2), 87–113.

Laville, H., Rigaud, J.-P., and Sackett, J., 1980. *Rock Shelters of the Perigord*. New York: Academic.

Lenoble, A., Bertran, P., and Lacrampe, F., 2008. Solifluction-induced modifications of archaeological levels: simulation based on experimental data from a modern periglacial slope and application to French Palaeolithic sites. *Journal of Archaeological Science*, **35**(1), 99–110.

Macphail, R. I., and Goldberg, P., 2000. Geoarchaeological investigation of sediments from Gorham's and Vanguard caves, Gibraltar: microstratigraphical (soil micromorphological and chemical) signatures. In Stringer, C. B., Barton, R. N. E., and Finlayson, J. C. (eds.), *Neanderthals on the Edge*. Oxford: Oxbow Books, pp. 183–200.

Macphail, R. I., Courty, M.-A., Hather, J., and Wattez, J., 1997. The soil micromorphological evidence of domestic occupation and stabling activities. In Maggi, R. (ed.), *Arene Candide: A Functional and Environmental Assessment of the Holocene Sequence: Excavations Bernabò Brea-Cardini (1940–50)*. Rome: Il Calamo. Memorie dell'Istituto Italiano di Paleontologia Umana, Vol. 5, pp. 53–88.

Macphail, R. I., and Goldberg, P., 2003. Gough's Cave, Cheddar, Somerset: microstratigraphy of the Late Pleistocene/earliest Holocene sediments. *Bulletin of the Natural History Museum: Geology*, **58**(Supplement S1), 51–58.

Mallol, C., Mentzer, S. M., and Wrinn, P. J., 2009. A micromorphological and mineralogical study of site formation processes at the Late Pleistocene site of Obi-Rakhmat, Uzbekistan. *Geoarchaeology*, **24**(5), 548–575.

Martini, J. E. J., 2000. Dissolution of quartz and silicate minerals. In Klimchouk, A., Ford, D. C., Palmer, A. N., and Dreybrodt, W. (eds.), *Speleogenesis. Evolution of Karst Aquifers*. Huntsville: National Speleological Society, pp. 171–174.

Meignen, L., Goldberg, P., and Bar-Yosef, O., 2007. The hearths at Kebara Cave and their role in site formation processes. In Bar-Yosef, O., and Meignen, L. (eds.), *Kebara Cave, Part 1*. Cambridge, MA: Peabody Museum of Archaeology and Ethnology, Harvard University, pp. 91–122.
Moriarty, K. C., McCulloch, M. T., Wells, R. T., and McDowell, M. C., 2000. Mid-Pleistocene cave fills, megafaunal remains and climate change at Naracoorte, South Australia: towards a predictive model using U-Th dating speleothems. *Palaeogeography Palaeoclimatology Palaeoecology*, **159** (1–2), 113–143.
Mylroie, J. E., 2005. Coastal caves. In Culver, D. C., and White, W. B. (eds.), *Encyclopedia of Caves*. Amsterdam: Elsevier, pp. 122–127.
Mylroie, J. E., and Carew, J. L., 2000. Speleogenesis in coastal and oceanic settings. In Klimchouk, A. B., Ford, D. C., Palmer, A. N., and Dreybrodt, W. (eds.), *Speleogenesis: Evolution of Karst Aquifers*. Huntsville: National Speleological Society, pp. 226–233.
Pickering, R., and Kramers, J. D., 2010. Re-appraisal of the stratigraphy and determination of new U-Pb dates for the Sterkfontein hominin site, South Africa. *Journal of Human Evolution*, **59**(1), 70–86.
Pickering, R., Hancox, P. J., Lee-Thorp, J. A., Grün, R., Mortimer, G. E., McCulloch, M., and Berger, L. R., 2007. Stratigraphy, U-Th chronology, and paleoenvironments at Gladysvale Cave: insights into the climatic control of South African hominin-bearing cave deposits. *Journal of Human Evolution*, **53**(5), 602–619.
Rolland, N., 2004. Was the emergence of home bases and domestic fire a punctuated event? A review of the Middle Pleistocene record in Eurasia. *Asian Perspectives*, **43**(2), 248–280.
Schiegl, S., Goldberg, P., Bar-Yosef, O., and Weiner, S., 1996. Ash deposits in Hayonim and Kebara caves, Israel: macroscopic, microscopic and mineralogical observations, and their archaeological implications. *Journal of Archaeological Science*, **23**(5), 763–781.
Shahack-Gross, R., Berna, F., Karkanas, P., and Weiner, S., 2004. Bat guano and preservation of archaeological remains in cave sites. *Journal of Archaeological Science*, **31**(9), 1259–1272.
Sherwood, S. C., and Chapman, J., 2005. The identification and potential significance of early Holocene prepared clay surfaces: examples from Dust Cave and Icehouse Bottom. *Southeastern Archaeology*, **24**(1), 70–82.
Sherwood, S. C., Driskell, B. N., Randall, A. R., and Meeks, S. C., 2004. Chronology and stratigraphy at Dust Cave, Alabama. *American Antiquity*, **69**(3), 533–554.
Skeates, R., 1997. The human uses of caves in east-central Italy during the Mesolithic, Neolithic and Copper Age. In Bonsall, C., and Tolan-Smith, C. (eds.), *The Human Use of Caves*. Oxford: Archaeopress. British Archaeological Reports, International Series, Vol. 667, pp. 79–86.
Springer, G. S., 2012. Clastic sediments in caves. In Culver, D. C., and White, W. B. (eds.), *Encyclopedia of Caves*. Amsterdam: Elsevier, pp. 134–140.
Straus, L. G., 1997. Convenient cavities: some human uses of caves and rockshelters. In Bonsall, C., and Tolan-Smith, C. (eds.), *The Human Use of Caves*. Oxford: Archaeopress. British Archaeological Reports, International Series, Vol. 667, pp. 1–8.
Tolan-Smith, C., and Bonsall, C., 1997. The human use of caves. In Bonsall, C., and Tolan-Smith, C. (eds.), *The Human Use of Caves*. Oxford: Archaeopress. British Archaeological Reports, International Series, Vol. 667, pp. 217–218.
Tsatskin, A., Weinstein-Evron, M., and Ronen, A., 1995. Weathering and pedogenesis of wind-blown sediments in the Mount Carmel caves, Israel. *Quaternary Proceedings*, **4**, 83–93.
Van Vliet-Lanoë, B., 1985. Frost effects in soils. In Boardman, J. (ed.), *Soils and Quaternary Landscape Evolution*. Chichester: Wiley, pp. 117–158.
Wadley, L., Sievers, C., Bamford, M., Goldberg, P., Berna, F., and Miller, C., 2011. Middle Stone Age bedding construction and settlement patterns at Sibudu, South Africa. *Science*, **334**(6061), 1388–1391.
Weiner, S., and Bar-Yosef, O., 1990. States of preservation of bones from prehistoric sites in the Near East: a survey. *Journal of Archaeological Science*, **17**(2), 187–196.
Weiner, S., Goldberg, P., and Bar-Yosef, O., 1993. Bone preservation in Kebara Cave, Israel using on-site Fourier transform infrared spectrometry. *Journal of Archaeological Science*, **20**(6), 613–627.
Weiner, S., Goldberg, P., and Bar-Yosef, O., 2002. Three-dimensional distribution of minerals in the sediments of Hayonim Cave, Israel: diagenetic processes and archaeological implications. *Journal of Archaeological Science*, **29**(11), 1289–1308.
White, W. B., 2000. Development of speleogenetic ideas in the 20th century: the modern period: 1957 to the present. In Klimchouk, A. B., Ford, D. C., Palmer, A. N., and Dreybrodt, W. (eds.), *Speleogenesis: Evolution of Karst Aquifers*. Huntsville: National Speleological Society, pp. 39–43.
White, W. B., and Culver, D. C., 2005. Cave, definition of. In Culver, D. C., and White, W. B. (eds.), *Encyclopedia of Caves*. Amsterdam: Elsevier, pp. 81–85.
Woodward, J. C., and Goldberg, P., 2001. The sedimentary records in Mediterranean rockshelters and caves: archives of environmental change. *Geoarchaeology*, **16**(4), 327–354.

Cross-references

Chemical Alteration
Chronostratigraphy
Colluvial Settings
Fourier Transform Infrared Spectroscopy (FTIR)
Hearths and Combustion Features
Kebara Cave
Mass Movement
Pastoral Sites
Scanning Electron Microscopy (SEM)
Soil Micromorphology
Trampling
X-ray Diffraction (XRD)

CERAMICS

Charles C. Kolb
Vienna, VA, USA
National Endowment for the Humanities, Washington, DC, USA

Introduction

Ceramics are among the tangible products of human culture that are relatively widespread among societies across the world. The innovation or adoption of ceramic objects provides significant and compelling questions for scholars, and ceramics, especially fragments of pottery called potsherds (sherds or shards), are one of the most common material objects that archaeologists encounter on surveys or excavations of Holocene archaeological sites, particularly over the past six millennia. In materials science, "ceramic" includes any solid made of inorganic compounds combining metallic and nonmetallic elements and generally possessing refractory and nonconducting properties, while "ceramics" in a nontechnical sense include varieties of fired-clay and siliceous bodies, such as earthenwares, stonewares, terra-cottas, china, and porcelain (Rice, 1987, 2015). Ceramic artifacts include many types and classes of object: domestic/utilitarian and ritual pottery containers; cooking, serving, and food storage vessels; figurines, spindle whorls, earspools, lamps, smoking pipes, tokens, medicinal pastilles, female pubic coverings, beehives, coffins, and other objects. The definition also embraces glass, bricks, ovens, architectural decorations (roof and floor tiles, cast sculptural forms), vitreous plumbing fixtures, sewer pipe, and molds (Matson, 1965; Kolb, 1989b, 2001, 2011).

The study of ceramics is a broad, highly diverse topic, and it is the subject of numerous scientific and popular books as well as journal articles. This contribution focuses initially on the relationships of geoarchaeology to clay and ceramic materials, then it summarizes the literature on archaeological ceramics, provides distinctions between ceramics and pottery, and reviews analytical methods used to interpret technological variables.

The importance of ceramic products

Potsherds are likely the most abundant macro-artifacts recovered archaeologically during the later periods of human existence, and in the main, they tend to be preserved almost as well as stone or lithic tools and their debris. Yet, it can be challenging to date ceramic materials accurately, determine their provenance or location of manufacture, and discern their intended original and subsequent uses. Fired and unfired clay figurines, not vessels made of clay, are the oldest known ceramic artifacts attributed to human fabrication; such small sculptures were created over 25,000 years ago in Eastern Europe according to current evidence (Vandiver et al., 1989; Farbstein et al., 2012). Nonetheless, pottery making is one of the oldest crafts known to humankind and was invented independently in different parts of the world, at different times, and within extremely diverse sociopolitical, economic, and ecological settings (Shelach, 2012; Wu et al., 2012). Scientific analysis of ceramic materials can inform us about technological changes that vary across space (synchronic) and through time (diachronic), craft specialization, and sociocultural, behavioral, economic, religious, and ideological roles and relationships within and between human societies. Hence, banal and unassuming ceramic artifacts such as potsherds provide a wealth of scientific and cultural information if the relevant data can be extracted and interpreted.

Geoarchaeology and ceramics

The term "geoarchaeology" was apparently coined by Karl Butzer in 1973, and it was a foundational component of his influential book *Archaeology as Human Ecology* (Butzer, 1982). Davidson and Shackley (1976) provided a traditional approach to the topic, while Waters (1996) documented the foundations of geoarchaeology in North America, emphasizing archaeological site matrices, alluvial environments and fluvial landscapes, glaciers, and cave and rock shelter formation. Rapp and Hill's *Geoarchaeology: The Earth-Science Approach to Archaeological Interpretation* (1998, 2006) was among the first textbooks to offer an integrated approach to geoarchaeology and focused on the direct use of geologic concepts and methods to solve archaeological problems and interpret archaeological records. Goldberg et al. (2001) and Goldberg and Macphail (2006) assessed geology and archaeology and provided case studies. In most other treatises on geoarchaeology, however, ceramics were subsidiary to ecological and site formation processes. A truly earth-science approach focused specifically upon ceramics began earlier, in the 1930s, with geologist Anna O. Shepard's research (1965), which integrated geology and archaeological ceramic data for the American Southwest and Mesoamerica. Scientific approaches to ceramic analysis encompassed a finer examination of the composition of ceramic artifacts and sherds to determine the source of the material and, through this, the possible location of manufacture. Major criteria that were examined included the composition of the clays and tempers (aplastics) used in the fabrication of the artifact being analyzed. Temper is an organic or inorganic material added to the clay during the production stage to achieve a particular quality in the paste (plastic, or malleable, material to be formed into a desired object) such as workability, drying and firing characteristics, and intended use, such as a cooking vessel that would undergo thermal stress.

Sources of information

Potters who fashion objects from clay are faced with technological choices throughout the fabrication process. These choices involve selection of clays and tempers, techniques of raw material preparation, forming methods and equipment, diversities of surface treatment, varieties of graphic and plastic decoration, as well as drying and firing procedures. The choices and selections that a potter makes are limited by environmental parameters, technological options, subsistence and economic factors, sociocultural contexts, political forms, religious and belief systems, as well as individual and group psychological or behavioral variables. These parameters are examined through methodological paradigms of ceramic ecology (Matson, 1965; Arnold, 1985; Rice, 1987, 2015) and the concept of *chaîne opératoire* wherein archaeological finds are understood as products of sequential processes of manufacture, use, and disposal (Scarcella, 2011). Matson's (1965) concept of ceramic ecology emphasizes a holistic assessment of pottery, beginning with the selection of raw materials, the fabrication of products and their distribution, the final uses, modifications, and discards of the ceramic object. The method and theory of ceramic studies has been expanded and enhanced (Arnold, 1985, 1993; Kolb, 1989a, 1997; Rice 1987, 2015) and extended in a revised form into the ethnographic literature through ceramic ethnoarchaeology (Kramer, 1985; Longacre, 1991). The relationships among these factors have been the subject of much discussion in the anthropological and archaeological literature, and they have led to the publication of voluminous numbers of books and journal articles in what is termed archaeological ceramics and ceramic ethnoarchaeology.

A recent examination of the scientific and anthropological periodical literature that focuses on ceramic studies illustrates the major journals that contain articles on the subject. The information (up to 2015) is summarized in Table 1. The publication of reports on ceramic analysis commenced early in the twentieth century with a concern for typology and classification, and the scientific analysis of ceramics began in the 1930s with thin-section petrography (TSP), expanding greatly with the advent of new physicochemical techniques following the development of radiocarbon dating in the late 1950s. Chemical and radiometric analyses of all forms of material culture in the 1970s and 1980s led to the creation of new journals for the publication of analytical results.

The data also indicate that two science-oriented journals, *Archaeometry* and the *Journal of Archaeological Science*, consistently publish contributions on ceramics in each issue, while *Geoarchaeology: An International Journal* reveals surprisingly fewer than might be expected. Other periodicals that occasionally publish ceramic studies include the *Journal of Archaeological Method and Theory* and the *Journal of Field Archaeology*. Relatively few journals are devoted exclusively to ceramic studies; the notable exceptions are the *Journal of Roman Pottery Studies* and the *Leiden Journal of Pottery Studies*. Two primary archaeological journals, the venerable *American Journal of Archaeology* of the American Institute of Archaeology and the British journal *Antiquity*, published a few scientific studies on ceramic materials beginning in the 1950s and more during the past two decades. Periodicals published by professional archaeological societies often contain articles on pottery analysis; these include *American Antiquity* and its newer sister journal, *Latin American Antiquity*, affiliated with the Society for American Archaeology, and the Society for Historical Archaeology's *Historical Archaeology*. The regionally oriented *North American Archaeologist* and *Midcontinental Journal of Archaeology*, as well as *World Archaeology*, occasionally present contributions on ceramic studies. Among other major professional organizations, the American Chemical Society, American Ceramic Society, and Materials Research Society, each have a publication series that focuses on archaeological ceramics.

Ceramics, Table 1 Ceramic studies in the major journals

Journal/publication (dates reviewed)[a]	Volume numbers	Ceramic articles n =
Archaeological and Anthropological Sciences (2009–2015)	1(1)–7(2)	4
Archaeomaterials (1986–1993) [ceased publication]	1(1)–7(3)	26
Archaeometry (1957–2015)	1(1)–57(3)	444
Geoarchaeology: An International Journal (1986–2015)	1(1)–30(3)	64
Journal of Anthropological Archaeology (1981–2015)	1(1)–40	34
Southwestern Journal of Anthropology (1945–1972)	1(1)–28(4)	8
Journal of Anthropological Research (1973–2015)	1(1)–71(2)	25
Journal of Archaeological Method and Theory (1994–2015)	1(1)–22(2)	26
Journal of Archaeological Research (1993–2015)	1(1)–23(2)	8
Journal of Archaeological Science (1974–2015)	1(1)–60	385
Journal of Archaeological Science: Reports (2015)	1–4	8
Journal of Field Archaeology (1974–2015)	1(1)–40(2)	90
Journal of Roman Pottery Studies (1986–2012)[b]	1–15	132
Newsletter of the Department of Pottery Technology		
[Leiden University] (1983–2002)	1–19	94
Leiden Journal of Pottery Studies (2004–2010) [ceased publication]	20–26	57
American Anthropologist (1888–2015)	1(1)–117(2)	33
American Antiquity (1935–2015)	1(1)–80(2)	196
Advances in Archaeological Practice: A Journal of the SAA (2013–2015)	1(1)–3(2)	5
American Journal of Archaeology (1897–2015)	1(1)–119(2)	284
Antiquity (1927–2015)	1(1)–89(345)	59
Bulletin of the American Schools of Oriental Research (1919–2015)	1–373	83
Historical Archaeology (1967–2015)	1–48(1)	86
International Journal of Historical Archaeology (1997–2015)	1(1)–19(2)	20
Latin American Antiquity (1990–2015)	1(1)–26(2)	49
Midcontinental Journal of Archaeology (1975–2015)	1(1)–40(2)	25
North American Archaeologist (1980–2015)	1(1)–36(3)	22
World Archaeology (1970–2014)	1(1)–47(3)	58
American Chemical Society: Advances in Chemistry Series		
Archaeological Chemistry (1974–2007)[b]	8 volumes	39
American Ceramic Society		
Ceramics and Civilization (1985–1998)[b, c]	8 volumes	101
Materials Research Society		
Materials Issues in Art and Archaeology (1988–2014)	10 volumes	115

[a]Data collected through June 2015
[b]Latest issue published
[c]Volume 8 (1998) is on glassmaking (the 16 articles are not included)

While Anna Shepard's *Ceramics for the Archaeologist* (1965) was the foundational handbook, Prudence Rice's *Pottery Analysis: A Sourcebook* (1987, 2015) still remains the most comprehensive volume yet available covering all aspects of ceramic materials, including raw materials, the properties of clays, pottery manufacture and use, and characterization studies.

For a materials science and engineering perspective, Carter and Norton's *Ceramic Materials: Science and Engineering* (2007) is invaluable.

The most recent reviews of the status of archaeological ceramic studies are by Tite (1999) and Kolb (1989b, 2001, 2011). Over the past four decades, there have been three distinct, discernible, but overlapping chronological phases of archaeological ceramic research: (1) an initial phase concerned predominantly with the documentation of variables of pottery manufacture, provenance, and physicochemical characterization; (2) a phase, derived in part from economic anthropology, with particular emphasis on the distribution and consumption of the finished products; and (3) a trend, building on the second phase, toward behavioral analyses and psychological meanings reflecting upon the potters and their products. Through all three phases, there has been a dynamic growth in the application of methods derived from the physical and biological sciences, so that the archaeometric toolkit has expanded dramatically in our ability, for example, to determine provenance and vessel contents. With few exceptions, the literature on archaeological pottery is particularistic, or narrowly focused, rather than holistic in that published reports provide in-depth assessments of production but lack consideration of consumption and distribution, and they rarely concern group or individual behaviors and sociocultural meanings (Lemonnier, 1993). The major compendia on archaeological ceramics consider raw materials selection and preparation, methods of pottery fabrication and surface treatments, and drying and firing procedures (Shepard, 1965; Rye, 1981; Rice, 1987, 2015; Sinopoli, 1991; Orton et al., 1993; Gibson and Woods, 1997; Orton and Hughes, 2013) but provide minimal or no discussion of pottery distribution, consumption, and the ultimate disposition of the artifacts.

There are substantial scientific studies of ceramic materials ranging from general treatments (Lambert, 1997) to handbooks or encyclopedic compendia (Ellis, 2000; Brothwell and Pollard, 2001; Maschner and Chippindale, 2005) and substantive assessments, some now dated (Rice, 1987; Henderson, 2000; Biswas, 2005). Recent volumes designed as an introduction to the breadth of archaeological chemistry include major works by Goffer (2007), Pollard et al. (2007), Pollard and Heron (2008), and Price and Burton (2011); see comparative reviews by Kolb (2009). Velde and Druc (1999) authored *Archaeological Ceramic Materials*, one of the few focusing on ancient ceramics. There are also a number of recently edited volumes on pottery analyses (Druc, 2001; Glascock, 2002; Glowacki and Neff, 2002; Jakes, 2002; Martinón-Torres and Rehren, 2008; Shortland et al., 2009). Rice (1987, 1996a, 1996b, 2015) provides a valuable review of the literature, while Neff's (1992) edited volume contains specific, in-depth views of the applications of a variety of these analyses. Materials science approaches also play a significant role in this phase and include "cautionary tales" about archaeological ceramic research (Bronitsky, 1986; Kolb, 1997). Pottery function is also a trait of this phase (Skibo, 1992, 2013; Rice 1996a) as is specialization and standardization (Rice, 1987, 1996b; Costin, 1991, 2005). Archaeometry and materials science are foci of edited works by Martinón-Torres and Rehren (2008), Quinn (2009), and Shortland et al. (2009).

Clay, ceramics, pottery, and other distinctions

The nature of clay

The distinctions between these terms are drawn primarily from Carter and Norton (2007), Goffer (2007), Pollard and Heron (2008), and Rice (1987). The word "clay" derives from the Old English *clǣġ* ("stiff, sticky earth"), from the Proto-Germanic *klajjaz* or *kli* ("to stick"), and from Proto-Indo-European *glei* ("to glue or stick together") and is ultimately related to the Greek word *gloios* ("sticky matter"), the Latin *glus* and *gluten* ("sticky matter"), and the Old Slavic *glina* ("clay") (Harper, 2015). "Clay" is effectively a generic term referring to a substance that incorporates one or more clay minerals in many combinations with traces of metallic oxides and organic matter. Clay is a naturally occurring material, and its constituent clay minerals are composed predominantly of fine-grained sheet silicates (or phyllosilicates) with grain sizes <2 μm that are chemically classified as hydrous aluminosilicates. All silicate minerals contain silicon and oxygen, and they comprise the largest and most significant class of rock-forming minerals, constituting about 90 % of the Earth's crust. Silicate minerals are classified on the basis of the structure of the silicate group and the strength of the Si–O bond. In the case of clay minerals, the structure is sheet-like, yet the extremely thin sheets several atoms thick break up into very small, submicroscopic crystals.

The introduction of water to a clay body provides sufficient lubrication to impart plasticity, which is defined as the ability of a material to deform under pressure yet maintain the new deformed shape when the pressure is released. As long as the plastic limit is reached for the particular clay mineral or admixture of minerals by the introduction of sufficient water, the platy clay crystals slide by one another and hold the position into which they are forced. Additional water will lower the yield strength, so that less force is required to deform the mass, until the liquid limit is reached and the clay begins to behave as a liquid.

The moisture required to reach the plastic limit and produce a plastic body is referred to as the "water of plasticity." When a clay object has been fashioned and left to dry, this water of plasticity evaporates in large measure, causing the paste to lose its plastic nature and become hard. When fired to a sufficiently high temperature, the crystal structure of the clay minerals making up such a hardened clay object breaks down, and the hydrous component of its mineral composition is driven off. The loss of this "water of crystallization" transforms the formerly clay object into an essentially artificial ceramic one that will no longer return to a plastic state with the addition of water (Rice, 2015).

Unlike stone sources, clay is a complex erosional product of rocks that were subjected to gradual chemical weathering over long periods of time. Because clays are widely distributed, they are relatively easy to find, extract, and process; their abundance also explains why earthenware products are found in nearly every part of the world. Clay deposits are generally made up of tiny clay mineral crystals (plus extraneous fine materials) that settled out of suspension in low-energy bodies of water such as lakes and rivers. Higher-energy flows and internal thermal currents tend to keep clays in suspension.

Clays are differentiated from other fine-grained soil substances based on grain size and mineralogy. Silts are fine-grained materials that do not include clay minerals. They generally have larger particle sizes than clays, but there is some overlap in particle size as well as other physical properties, so many natural deposits can include both silts and clays. Primary clays are located at the site of formation, while secondary clay deposits have been relocated by erosion and possibly lengthy transport by natural processes from their primary location. There are approximately 30 different types of "pure" clay minerals in these categories (Moore and Reynolds, 1997), but most "natural" clay deposits are mixtures of these types, with additions of other weathered minerals (Rice, 2015).

The distinctions between silt and clay and between the different types of clay vary by academic discipline. Geologists and soil scientists consider the separation between clay and silt to occur at a particle size of 2 μm (clays being finer than silts), sedimentologists often use 4–5 μm, and colloid chemists use 1 μm. Materials scientists and geotechnical engineers distinguish between silts and clays based on soil plasticity properties. Categorized by their atomic composition and molecular structure, there are three or four main groups of clays: kaolinite, montmorillonite-smectite, illite, and chlorite. Chlorites are not always considered clay, sometimes being classified as a separate group within the phyllosilicates. Other names for clay sediments exist in common usage. "Kaolin" is sometimes referred to as China clay because it was initially identified in China; "ball clay" is an extremely plastic, fine-grained sedimentary clay, which is largely composed of the clay mineral kaolinite and may contain some organic matter; "bentonite" is a highly plastic clay composed mostly of the clay mineral montmorillonite that absorbs water and is used as a mold binder in the manufacture of sand castings; "fire clay" differs from kaolin in having a slightly higher percentage of fluxes (components that promote melting at lower temperatures than the pure material), is quite plastic, and is highly heat resistant. "Stoneware clay" is fine grained and used to create a ceramic with characteristics lying between fire clay and ball clay and is heat resistant in order to produce the hard and watertight ceramic called stoneware (Rice, 1987; Guggenheim and Martin, 1995; Kolb, 2011; ASTM, 2015). Clays, the raw materials of pottery making, chemical and mineralogical definitions, and the clay/water system are further elaborated by Rice (1987, 2015).

The word "ceramic" comes from the Greek word *κεραμικός*, keramikos ("of pottery" or "for pottery") and from *κέραμος*, keramos ("potter's clay, tile, pottery") (Harper, 2015). It is an "artificial stone" created by humans that combines earth/clay, water, fire, and air – the four basic elements identified by the ancient Greeks. The terms ceramics, pottery, and earthenware are sometimes interchangeable, but although these are all synthetic materials, there are important distinctions and discrete definitions that require explanation. A ceramic is an inorganic, nonmetallic solid prepared by the action of heat and subsequent cooling. Ceramic materials may have a crystalline or partly crystalline structure, or they may be amorphous (e.g., a glass). Because most common ceramics are crystalline, the definition of ceramic is often restricted to inorganic crystalline materials, as opposed to the noncrystalline glasses. Pottery as a generic term includes earthenware, stoneware, and porcelain. ASTM Standard C 242-01: "Standard Terminology of Ceramic Whitewares and Related Products" (ASTM, 2015) defines pottery as "all fired ceramic wares that contain clay when formed, except technical, structural, and refractory products." There are four major types of pottery:

- *Terra-cotta* is a very porous, lightweight pottery developed in Southwest Asia ca. 6000 BP and fired to <850 °C.
- *Earthenware* has a continuous history from the Neolithic period to the present and was made from clays that were fired at temperatures >950 °C in open bonfires or pits. Majolica and faience are glazed earthenwares (Tite and Shortland, 2008).
- *Stoneware* was created beginning as early as the fifteenth century BCE in China, and especially since the seventh century CE, and coincides with the innovation of kilns that could be fired at higher temperatures, 1200–1300 °C.
- *Porcelain* is made from "China clay" and fired at 1300 °C. It was first made in China during the Tang Dynasty (618–906 CE).

"Greenware" refers to unfired objects in a soft and malleable "plastic" form. "Leather-hard" refers to a partially dry, pliable clay body that has approximately 15 % moisture content and represents the ideal stage for trimming and handle attachment. "Bone-dry" refers to clay bodies after glaze or biscuit firing with moisture content near 0 %. "Biscuit" connotes a shaped object that has been fired in the kiln for the first time. "Glost fired" is the final stage when a glaze may be applied.

Ceramic research

Research on ceramics has, in the main, four goals: (1) description and characterization; (2) provenance; (3) ascertaining chronology; and (4) explanation, inference, and/or the testing of hypotheses.

Materials scientists and archaeologists are concerned with research design parameters, such as sampling and analytical or statistical procedures. Likewise, they expend time and effort in characterization studies of the physical properties of pottery (examining color, texture/microstructure, porosity/permeability, luster, density, mechanical and thermal properties), mineralogical composition (using petrography and X-ray diffraction), chemical content (using spectroscopy and microprobe analysis), structural characteristics (using electron microscopy and radiography), and contents and residues (using scanning electron microscopy and varied chemical analyses). Aspects of manufacturing/forming methods include tool use, form/shape analyses, surface modifications and drying, prefired and/or postfired decoration, and firing. Quantification of dimensions, volume, shape, function/use analyses, and contexts/associations is also of great cultural significance. Most archaeologists must work in some way with ceramic relative chronology, as it is essential to chronological control in many archaeological sites, but some specialists are particularly focused upon "absolute" or chronometric techniques of dating (archaeomagnetic, thermoluminescence, and radiocarbon analyses) or the use of varied methods in the authentication of objects.

Description and characterization

The process of pottery manufacture, from obtaining raw materials through firing and uses, is detailed by Rice (1987, 2015) and summarized by Tite (1999). The former author also reviews the important concepts of firing loss rates and fuel consumption and costs. Sheehy (1988) is among the few scholars to have examined clay/fuel ratios from archaeological and ethnoarchaeological perspectives. Vessel forms, technologies, and properties related to fabrication and the identification of use are well documented by Rice (1987), who also has summarized decorative styles and stylistic analyses (see also Cumberpatch and Blinkhorn, 1997). Use alteration, mentioned by Tite (1999), has been detailed by Skibo (2013). An assessment of residue analysis is also provided by Rice (1987) and Skibo (1992, 2013). Organic residue analysis (ORA) involves biomolecular studies, notably employing gas chromatography (GC), gas chromatography-mass spectrometry (GC-MS), and gas chromatography-combustion-isotope ratio mass spectrometry (GC-C-IRMS) as methods of extraction to evaluate lipids and other residues.

Colors of ceramic materials are normally described in the Munsell Color System (2009); for an historical assessment, see also Nickerson (1976) and Kuehni (2002). Clay identification is sometimes determined by a process of refiring the ceramic and assigning a color to it using Munsell Soil Color notation.

By estimating both the clay and temper compositions, and locating a region where both are known to occur, an assignment of the materials' origin can be made, leading to the identification of potential sites of manufacture. This process is referred to as sourcing, and the location of raw material extraction and/or production of the ceramic object is called its provenance. Mechanical and thermal properties and the mineralogical and chemical characterization of ceramic materials can also be determined (Rapp, 2002; Carter and Norton, 2007; ASTM, 2015). The varied types of physicochemical characterization studies conducted on ceramics have been summarized by Rice (1987, 1996b) and Kolb (2014), while Neff's (1992) edited volume provides specific, in-depth views of the applications of a variety of these analyses. Pottery function and use analyses are added to the bibliography (Skibo 1992, 2013; Rice 1996a), as is specialization and standardization (Rice, 1987, 1996b; Costin, 1991, 2005).

Thin-section studies (TSP: thin-section petrography) in archaeology, also termed optical mineralogy or optical petrography, date to the 1930s with Shepard's research (1965). It is the "classic" approach and, although tedious and time consuming, provides data on specimen compositions that bulk analyses such as INAA cannot provide. There is a voluminous literature (Philpotts, 1989; Humphries, 1992; Glazner et al., 1997; Tite, 1999; Clarke and Eberhardt, 2002; Reedy, 2008; Quinn, 2009). Kolb provides examples of analyses and cautionary tales (1997, 2001, 2008), while Reedy's current research focuses on digital and 3D imaging of ceramic thin sections (2012); radiographic procedures are summarized by Lang and Middleton (2005).

The primary physicochemical methods used in ceramic analysis include:

AAS: atomic absorption spectroscopy – superseded in the last decade by XRF
EPMA: electron probe microanalysis
INAA/NAA: instrumental neutron activation analysis
M/S: Mössbauer (German: Mößbauer) spectroscopy
TSEM: transmission scanning electron microscopy
X-ray milliprobe
X-ray radiography
XRF: X-ray fluorescence

A persistent difficulty within archaeological ceramic analysis is the study of whole assemblages from both a compositional and technological perspective. Existing techniques, such as TSP microscopy, ICP-MS, and INAA, "struggle" to integrate compositional datasets with the textural information that is crucial for reconstructing technological choices. The latter two provide chemical compositions, while TSP shows structural/textural evidence. However, advances in automated scanning electron microscopy with linked energy-dispersive spectrometers (SEM-EDS) create the potential to offer a seamless combination of textural and mineralogical data in which textural information can be accompanied by the acquisition of energy-dispersive elemental spectra. Mineral quantification using QEMSCAN® (quantitative evaluation of minerals by scanning electron microscopy) technology and compositional mapping allows standardized comparison of diverse datasets to address wider issues of social interaction within the ancient world. A typical analysis involves the collection of more than 500,000 individual points on a sample surface. For ceramic materials, this method offers an attractive visual representation of the texture as well as the mineralogical components. The components of the matrix and temper are commonly recognizable, and the analysis can reveal fine structures that are not visible by the naked eye. Automated SEM-EDS refines petrographic descriptions but also provides unique insight into clay mineral composition and clay mixing; mixtures of different clays combined to achieve specific working properties represent a traditionally difficult behavior on the part of potters to identify analytically (Hilditch et al., 2012).

Methods of determining provenance

Provenance studies have been conducted on earthenware, stoneware, protoporcelain, and porcelain, but few chemical studies have directly linked pottery vessels with specific clay sources. Clays may be transported long distances from sources to distant production workshops, making those sources difficult to trace. They may contain naturally occurring organic or inorganic aplastics that were removed prior to use through levigation (the separation of coarse matter by suspending the fine fraction in water), and organic or inorganic materials may be introduced purposefully as temper or unintentionally during the preparation of the clay. Heterogeneous clays from different sources may also be brought together to achieve specific properties and thoroughly mixed during the wedging process wherein air is forced out of the clay prior to forming. The size and complexity of the manufacturing process may vary – from simple contexts such as household production by one potter to larger group efforts by multiple artisans, each responsible for one step in a multiphase process, to the most complicated situations presented by a factory or industrial level of fabrication – and these variations pose challenges to one's ability to define ceramic provenance precisely (Rice, 1987, 2015; Neff, 2002; Goldstein et al., 2003; Pollard and Heron, 2008; Shackley, 2011; Kolb, 2014). The following list of methods that have been used to determine provenance derives from a review of the volumes and journal literature in Table 1. As in physicochemical analyses (discussed above), each method has advantages and disadvantages.

AAS: Atomic absorption spectroscopy: Superseded in the last decade by XRF.
EPMA: Electron probe microanalysis: Similar to SEM which has a higher sensitivity.
FTIR: Fourier transform infrared spectrometry.
GC: Gas chromatography, HT-GC (high-temperature GC), HT-GC-MS (HT-GC with mass spectrometry): Residues on or in ceramics.
ICP-AES: Inductively coupled plasma (spectroscopy)-atomic emission spectroscopy.
INAA/NAA: Instrumental neutron activation analysis.
ICP-MS: Inductively coupled plasma-mass spectroscopy: It is replacing INAA (Speakman and Neff, 2005).
ICP-OES: Inductively coupled plasma-optical emission spectrometry.
LA-ICP-MS: Laser ablation-inductively coupled plasma (spectroscopy)-mass spectrometry, TOF-LA-ICP-MS (time-of-flight LA-ICP-MS).
LC: Liquid chromatography, LC-MS (LC with mass spectrometry): Residues on ceramics.
M/S: Mössbauer (German: Mößbauer) spectroscopy.
OCL: Optical cathodoluminescence.
PIXE/PIGME: Proton-induced X-ray emission/proton-induced gamma ray emission.
R/S: Raman spectroscopy.
SEM: Scanning electron microscopy, SEM-EDS (SEM with energy-dispersive spectrometers), SEM-WDS (SEM with wavelength-dispersive X-ray spectroscopy).
TSP: Thin-section petrography, OM (optical mineralogy), and OP (optical petrography).
XRD: X-ray diffraction.
XRF: X-ray fluorescence, ED-XRF (energy-dispersive-XRF): Portable (or hand-held) X-ray fluorescence (pXRF) spectrometry has become common for the geochemical characterization of ceramics.
XRPD: X-ray powder diffraction.

Methods of ascertaining chronology

Chronology is a fundamental component of scientific and humanistic inquiry. There are two ways to establish chronology: methods of *relative dating* (ascertaining the correct order of the events) and *absolute or chronometric dating* (quantifying the measurement of time in terms of years or other fixed units). Relative dating may be determined from (1) sequence dating through seriation (changes in artifact form, function, or style through time), (2) stratigraphic analysis (geological stratigraphy based upon the "Law of Superposition"), and (3) cross-dating. Chronometric dating may rely upon (1) historic or written records, (2) non-radiometric scientific studies (such as dendrochronology, thermoluminescence, or obsidian hydration dating techniques), (3) radiometric analyses (radiocarbon and uranium series dating, e.g., which rely upon the decay of unstable parent isotopes into stable daughter forms), and (4) biochemical analyses (notably by amino acid racemization). Chronometric dating that assigns specific dates or date ranges in calendar years to artifacts and other archaeological finds is critical to ceramic studies. Most of the chronometric dating methods above do not date ceramics directly; however, they provide an age for other materials that must be recovered in close temporal association with the ceramics. Since the 1950s, radiocarbon dating has been the most significant and commonly employed chronometric method in archaeology, but ceramic materials must be associated with appropriately datable samples in order to be assigned the same age. The analysis of carbonaceous residues adhering to ceramic cooking pots has been used to some advantage.

There are two types of luminescence dating techniques: optical dating (notably optically stimulated luminescence or OSL) used on sediments and thermoluminescence (TL) which can be employed on a variety of burned materials including heat-treated flint, sediments, and pottery. Thermoluminescence is now commonly used in the authentication of old ceramic wares, for which it gives the approximate date of the last firing (Aitken, 1990; Taylor and Aitken, 1997). When a small sample of ancient pottery is heated, it glows with a faint blue light, called thermoluminescence. During its lifetime, the pottery absorbs radiation from its environment as well as internal radiation sources, and this radiation causes an increase in energy within the fabric of the ceramic due to electrons trapped at higher-energy states after having been displaced from their regular atomic orbits by the radiation. The older the pottery, the more radiation it has absorbed, and the brighter the pottery sample glows when reheated in the laboratory. By measuring the TL, it is possible to calculate how much radiation has been absorbed. This information can then be used to compute the approximate age of the pottery.

Rehydroxylation (RHX) dating has been proposed as a new chronometric dating tool for use on archaeological fired-clay ceramics (Wilson et al., 2009, 2014). The technique relies upon the propensity of reheated porous ceramic objects to regain water through a two-stage process (rehydration and RHX), where the kinetics of the second stage have been shown to follow a $(\text{time})^{1/4}$ power law at temperatures of 13–50 °C. RHX is self-calibrating, so the reaction rate adjusts according to differences in firing temperature, mineralogy, and microstructure. An empirical equation accounting for the effects of burial in archaeological sites and temperature history has been developed to describe the observed ceramic's rehydration and RHX behavior. RHX can provide a date of manufacture for archaeological ceramics by measuring the lifetime mass gain. The technique shows great promise, and after additional research, it could become an important archaeometric tool.

Emerging analytical techniques

Close-range digital photogrammetry is applicable to pottery (Matthews, 2008). The technique is used to derive 3D measurements from stereoscopic image overlap and has been shown to have extensive applications (Verhoeven, 2011). Close-range photogrammetry (CRP) refers to the collection of photography from a lesser distance than traditional aerial photogrammetry. It is similar to 3D scanning, in that both techniques are noncontact, fast, and accurate methods for recording objects in three dimensions. Images captured from a distance of 0.5–2 m will have a pixel resolution of 60–250 μm and will potentially produce a 3D model with a point spacing of approximately 0.5–1 mm.

Reflectance transformation imaging (RTI) (Webb and Wachowiak, 2011) is a relatively new method of digital documentation being increasingly utilized as an effective means of object documentation, and it is ideal for ceramic vessels. The process consists of capturing multiple digital images (typically between 40 and 64) of a stationary object from a fixed camera position. For each image captured, the object is illuminated using a single light source at a fixed distance and luminance. Employing a "stack" of images, each with a different but known light position, a per-pixel reflectance function can be mathematically estimated using a method known as polynomial texture mapping (PTM).

Experimental archaeology

Experimental archaeology and ceramic replication (Mathieu, 2002) are well-known methods designed to generate and test hypotheses based upon archaeological source material, the goal being to replicate past processes. The branch has four categories: (1) controlled replication of recovered artifacts or the reconstruction of known activities; (2) testing the validity of methodological assumptions by applying them to known data; (3) contextual experimentation, such as burying modern replicas and/or ecofacts for varying lengths of time to assess postdepositional effects on them; and (4) ceramic ethnographic or ethnoarchaeological data. Closely related is "reverse engineering," exemplified by Vandiver (2005), which links archaeological materials research and conservation science.

Databases

Digital data analysis and the creation of data bases often involve a transition from analog to searchable digital formats (Levy, 2012).

POTSHERD: Atlas of Roman Pottery (Tyers, 2012) is a collection of Web pages on archaeological pottery principally of the Roman period (first century BCE to fifth century CE) in Britain and Western Europe. The database includes an introductory atlas containing descriptions and distribution maps of types of Roman ceramics, lists of wares by class (tablewares, cooking wares, transport amphorae, etc.), and source (Roman province of origin).

The *Pottery Informatics Query Database* (PIQD) (Levy, 2012) provides for the digital preservation and analysis of ceramic collections, including 2D and 3D data. The initial focus is on the Iron Age Levant, 1200–500 BCE.

The *Diyala Database* (Oriental Institute, 2012) has published all archaeological materials from the Diyala Expedition in ancient Mesopotamia (modern Iraq). More than 15,000 artifacts including pottery and cuneiform tablets, as well as archival materials, object registers, field diaries, photographs, site plans, and correspondence were scanned, object descriptions entered into database tables, and new images of artifacts taken at the Oriental Institute Museum were inserted. The searchable Web-accessible database integrates all of these data formats. Employing high-resolution three-dimensional scans (up to 60 µm resolution) may allow many future projects to proceed by manipulating the digital rather than physical versions of ceramic objects.

Bibliography

Aitken, M. J., 1990. *Science-Based Dating in Archaeology*. London: Longman.

Arnold, D. E., 1985. *Ceramic Theory and Cultural Process*. Cambridge: Cambridge University Press.

Arnold, D. E., 1993. *Ecology and Ceramic Production in an Andean Community*. Cambridge: Cambridge University Press.

ASTM (American Society for Testing and Materials), 2015. *ASTM C242-15, Standard Terminology of Ceramic Whitewares and Related Products*. West Conshohocken: ASTM International. www.astm.org.

Biswas, A. K., 2005. *Science in Archaeology and Archaeo-Materials*. New Delhi: D. K. Printworld.

Bronitsky, G., 1986. The use of materials science techniques in the study of pottery construction and use. *Advances in Archaeological Method and Theory*, **9**, 209–276.

Brothwell, D. R., and Pollard, A. M., 2001. *Handbook of Archaeological Sciences*. Chichester: Wiley.

Butzer, K. W., 1982. *Archaeology as Human Ecology: Method and Theory for a Contextual Approach*. Cambridge: Cambridge University Press.

Carter, C. B., and Norton, M. G., 2007. *Ceramic Materials: Science and Engineering*. New York: Springer.

Clarke, A. R., and Eberhardt, C. N., 2002. *Microscopy Techniques for Materials Science*. Boca Raton: CRC Press.

Costin, C. L., 1991. Craft specialization: issues in defining, documenting, and explaining the organization of production. *Archaeological Method and Theory*, **3**, 1–56.

Costin, C. L., 2005. Craft production. In Maschner, H. D. G., and Chippindale, C. (eds.), *Handbook of Archaeological Methods*. Lanham: Altamira Press, pp. 1034–1107.

Cumberpatch, C. G., and Blinkhorn, P. (eds.), 1997. *Not so Much a Pot, More a Way of Life: Current Approaches to Artefact Analysis in Archaeology*. Oxford: Oxbow Books. Oxbow Monograph, 83.

Davidson, D. A., and Shackley, M. L., 1976. *Geoarchaeology: Earth Science and the Past*. Boulder: Westview Press.

Druc, I. C. (ed.), 2001. *Archaeology and Clays*. Oxford: Hedges. British Archaeological Reports International Series, 942.

Ellis, L. (ed.), 2000. *Archaeological Method and Theory: An Encyclopedia*. New York: Garland.

Farbstein, R., Radić, D., Brajković, D., and Miracle, P. T., 2012. First Epigravettian ceramic figurines from Europe (Vela Spila, Croatia). *PLoS ONE*, **7**(7), e41437, doi:10.1371/journal.pone.0041437.

Gibson, A. M., and Woods, A., 1997. *Prehistoric Pottery for the Archaeologist*, 2nd edn. London: University of Leicester Press.

Glascock, M. D. (ed.), 2002. *Geochemical Evidence for Long-Distance Exchange. Scientific Archaeology for the Third Millennium*. Westport: Bergin and Garvey.

Glazner, A. F., Ratajeskie, K., and Virtual Geology Project, 1997. *Atlas of Igneous and Metamorphic Rocks, Minerals, and Textures*. Chapel Hill: Department of Geology, University of North Carolina. http://leggeo.unc.edu/Petunia/IgMetAtlas/mainmenu.html.

Glowacki, D. M., and Neff, H. (eds.), 2002. *Ceramic Production and Circulation in the Greater Southwest: Source Determination by INAA and Complementary Mineralogical Investigations*. Los Angeles: Cotsen Institute of Archaeology, University of California Los Angeles. Institute of Archaeology Monograph, 44.

Goffer, Z., 2007. *Archaeological Chemistry*, 2nd edn. Hoboken: Wiley-Interscience.

Goldberg, P., and Macphail, R. I., 2006. *Practical and Theoretical Geoarchaeology*. Malden: Blackwell.

Goldberg, P., Holliday, V. T., and Ferring, C. R., 2001. *Earth Sciences and Archaeology*. New York: Kluwer/Plenum Publishers.

Goldstein, J. I., Newbury, D. E., Echlin, P., Joy, D. C., Lyman, C. E., Lifshin, E., Sawyer, L., and Michael, J. R., 2003. *Scanning Electron Microscopy and X-Ray Microanalysis: A Text for Biologists, Materials Scientists, and Geologists*, 3rd edn. New York: Kluwer/Plenum Publishers.

Guggenheim, S., and Martin, R. T., 1995. Definition of clay and clay mineral; joint report of the AIPEA nomenclature and CMS nomenclature committees. *Clays and Clay Minerals*, **43**(2), 255–256.

Harper, D., 2015. Online Etymology Dictionary. http://www.etymonline.com/?l=a.

Henderson, J., 2000. *The Science and Archaeology of Materials: An Investigation of Inorganic Materials*. London: Routledge.

Hilditch, J., Pirrie, D., Knappett, C., Momigliano, N., and Rollinson, G., 2012. Taking the coarse with the fine: the application of automated SEM-EDS with QEMSCAN® to ceramic assemblages in the Bronze Age Aegean. Paper presented at Insight from Innovation: New Light on Archaeological Ceramics conference, Southampton University, 19–21 October 2012. http://www.southampton.ac.uk/innovationconference/conference/.

Humphries, D. W., 1992. *The Preparation of Thin Sections of Rocks, Minerals, and Ceramics*. Oxford: Oxford University Press.

Jakes, K. A. (ed.), 2002. *Archaeological Chemistry: Materials, Methods, and Meaning*. Washington, DC: American Chemical Society. ACS Symposium Series, 831.

Kolb, C. C., 1989a. Ceramic ecology in retrospect: a critical review of methodology and results. In Kolb, C. C. (ed.), *Ceramic Ecology, 1988: Current Research on Ceramic Materials*. Oxford: British Archaeological Reports. British Archaeological Reports, International Series, 513, pp. 261–375.

Kolb, C. C., 1989b. The current status of ceramic studies. In Kolb, C. C (ed.), *Ceramic Ecology, 1988: Current Research on Ceramic Materials*. Oxford: British Archaeological Reports. British Archaeological Reports, International Series, 513, pp. 377–421.

Kolb, C. C., 1997. Analyses of archaeological ceramics from Classic period Teotihuacán Mexico, A.D. 150–750. In Druzik, J. R., Merkel, J. F., Stewart, J., and Vandiver, P. B. (eds.), *Materials Issues in Art and Archaeology V*. Pittsburgh: Materials Research Society. MRS Symposium Proceedings, 462, pp. 247–262.

Kolb, C. C., 2001. Comments on 'Technological choices in ceramic production'. *Archaeometry*, **42**(1), 1–76. Archaeometry, **43**(2), 273–277.

Kolb, C. C., 2008. Prehistoric ceramics of northern Afghanistan: neolithic through the Iron Age. In Vandiver, P., Casadio, F., McCarthy, B., Tykot, R. H., and Sil, J. L. R. (eds.), *Materials Issues in Art and Archaeology VIII*. Pittsburgh: Materials Research Society. MRS Symposium Proceedings, 1047, pp. 147–174.

Kolb, C. C., 2009. Comparative review of three books on archaeological chemistry: *Analytical Chemistry in Archaeology* (A. M. Pollard, C. M. Batt, B. Stern, and S. M. M. Young; New York: Cambridge University Press, 2007); *Archaeological Chemistry*, 2nd ed. (A. M. Pollard and C. Heron; Cambridge, UK: RSC Publishing, 2008); and *Archaeological Chemistry*,

2nd ed. (Z. Goffer; Hoboken, NJ: Wiley-Interscience, 2007). *SAS* [*Society for Archaeological Sciences*] *Bulletin*, **32**(1), 22–25.
Kolb, C. C., 2011. *Chaîne opératoire* and ceramics: classifications and typology, archaeometry, experimental archaeology, and ethnoarchaeology. In Scarcella, S. (ed.), *Archaeological Ceramics: A Review of Current Research*. Oxford: Archaeopress. British Archaeological Reports, International Series S2193, pp. 5–19.
Kolb, C. C., 2014. Provenance studies in archaeology. In Smith, C. (ed.), *Encyclopedia of Global Archaeology*. New York: Springer, pp. 6172–6181.
Kramer, C., 1985. Ceramic ethnoarchaeology. *Annual Review of Anthropology*, **14**, 77–102.
Kuehni, R. G., 2002. The early development of the Munsell system. *Color Research and Application*, **27**(1), 20–27.
Lambert, J. B., 1997. *Traces of the Past: Unraveling the Secrets of Archaeology through Chemistry*. Reading: Perseus Books.
Lang, J., and Middleton, A. (eds.), 2005. *Radiography of Cultural Material*, 2nd edn. Amsterdam: Elsevier.
Lemonnier, P., 1993. Introduction. In Lemonnier, P. (ed.), *Technological Choices: Transformations in Material Culture Since the Neolithic*. London: Routledge, pp. 1–35.
Levy, T., 2012. *Pottery Informatics Query Database (PIQD)*. San Diego: University of California. http://adaa.ucsd.edu/PIQD (Iron Age Levant, 1200–500 BCE).
Longacre, W. A. (ed.), 1991. *Ceramic Ethnoarchaeology*. Tucson: University of Arizona Press.
MacKenzie, W. S., and Guilford, C., 1980. *Atlas of Rock-forming Minerals in Thin Section*. New York: Longman.
Martinón-Torres, M., and Rehren, T. (eds.), 2008. *Archaeology, History, and Science: Integrating Approaches to Ancient Materials*. Publications of the Institute of Archaeology, University College London. Walnut Creek: Left Coast Press.
Maschner, H. D. G., and Chippindale, C., 2005. *Handbook of Archaeological Methods*. Lanham: AltaMira Press. 2 vols.
Mathieu, J. R. (ed.), 2002. *Experimental Archaeology, Replicating Past Objects, Behaviors, and Processes*. Oxford: Archaeopress. British Archaeological Reports, International Series, 1035.
Matson, F. R., 1965. Ceramic ecology: an approach to the study of early cultures of the Near East. In Matson, F. R. (ed.), *Ceramics and Man*. Chicago: Aldine. Viking Fund Publications in Anthropology, 41, pp. 202–217.
Matthews, N. A., 2008. *Aerial and Close Range Photogrammetric Technology: Providing Resource Documentation, Interpretation, and Preservation*. Denver: U.S. Department of the Interior, Bureau of Land Management. Technical Note, 428.
Moore, D. M., and Reynolds, R. C., Jr., 1997. *X-Ray Diffraction and the Identification and Analysis of Clay Minerals*, 2nd edn. Oxford: Oxford University Press.
Munsell Color, 2009. *Munsell Soil Color Charts*, revised edition. Grand Rapids: Munsell Color.
Neff, H. (ed.), 1992. *Chemical Characterization of Ceramic Pastes in Archaeology*. Madison: Prehistory Press. Monographs in World Archaeology, 7.
Neff, H., 2002. Quantitative techniques for analyzing ceramic compositional data. In Glowacki, D. M., and Neff, H. (eds.), *Ceramic Production and Circulation in the Greater Southwest: Source Determination by INAA and Complementary Mineralogical Investigations*. Los Angeles: Cotsen Institute of Archaeology, University of California Los Angeles. Institute of Archaeology Monograph, 44.
Nickerson, D., 1976. History of the Munsell color system, company, and foundation. *Color Research and Application*, **1**(3), 121–130.
Oriental Institute, 2012. *Diyala Archaeological Database (DiyArDa)*. Chicago: Oriental Institute, University of Chicago Publication and Research Project. http://diyalaproject.uchicago.edu/pls/apex/f?p=102:111:1627493516795901.
Orton, C., and Hughes, M., 2013. *Pottery in Archaeology*, 2nd edn. Cambridge: Cambridge University Press. Cambridge Manuals in Archaeology.
Orton, C., Tyers, P., and Vince, A. G., 1993. *Pottery in Archaeology*. Cambridge: Cambridge University Press. Cambridge Manuals in Archaeology.
Philpotts, A. R., 1989. *Petrography of Igneous and Metamorphic Rocks*. Englewood Cliffs: Prentice-Hall.
Pollard, A. M., and Heron, C., 2008. *Archaeological Chemistry*, 2nd edn. Cambridge: RSC Publishing (The Royal Society of Chemistry).
Pollard, A. M., Batt, C., Stern, B., and Young, S. M. M. (eds.), 2007. *Analytical Chemistry in Archaeology*. Cambridge: Cambridge University Press. Cambridge Manuals in Archaeology.
Price, T. D., and Burton, J. H., 2011. *An Introduction to Archaeological Chemistry*. New York: Springer.
Quinn, P. S. (ed.), 2009. *Interpreting Silent Artefacts: Petrographic Approaches to Archaeological Ceramics*. Oxford: Archaeopress.
Rapp, G. R., 2002. *Archaeomineralogy*. Berlin: Springer.
Rapp, G. R., and Hill, C. L., 1998. *Geoarchaeology: The Earth-Science Approach to Archaeological Interpretation*. New Haven: Yale University Press.
Rapp, G. R., and Hill, C. L., 2006. *Geoarchaeology: The Earth-Science Approach to Archaeological Interpretation*, 2nd edn. New Haven: Yale University Press.
Reedy, C. L., 2008. *Thin-Section Petrography of Stone and Ceramic Cultural Materials*. London: Archetype.
Reedy, C. L., 2012. Image analysis-aided light microscopy of glazed ceramics: identifying technological innovation and style. *Studies in Conservation*, **57**(S1), S227–S233.
Rice, P. M., 1987. *Pottery Analysis: A Sourcebook*. Chicago: University of Chicago Press.
Rice, P. M., 1996a. Recent ceramic analysis: 1. Function, style, and origins. *Journal of Archaeological Research*, **4**(2), 133–163.
Rice, P. M., 1996b. Recent ceramic analysis: 2. Composition, production, and theory. *Journal of Archaeological Research*, **4**(3), 165–202.
Rice, P. M., 2015. *Pottery Analysis: A Sourcebook*, 2nd edn. Chicago: University of Chicago Press.
Rye, O. S., 1981. *Pottery Technology: Principles and Reconstruction*. Washington, DC: Taraxacum. Manuals in Archaeology, 4.
Scarcella, S. (ed.), 2011. *Archaeological Ceramics: A Review of Current Research*. Oxford: Archaeopress. British Archaeological Reports, International Series, S2193.
Shackley, M. S. (ed.), 2011. *X-Ray Fluorescence Spectrometry (XRF) in Geoarchaeology*. New York: Springer.
Sheehy, J. J., 1988. Ceramic ecology and the clay/fuel ratio: modeling fuel consumption in Tlajinga 33, Teotihuacán, Mexico. In Kolb, C. C. (ed.), *Ceramic Ecology Revisited, 1987: The Technology and Socioeconomics of Pottery*. Oxford: British Archaeological Reports. British Archaeological Reports, International Series, 436, pp. 199–226.
Shelach, G., 2012. On the invention of pottery. *Science*, **336**(6089), 1644–1645.
Shepard, A. O., 1965. *Ceramics for the Archaeologist*, revised edition. Publication 609. Washington, DC: Carnegie Institution of Washington.
Shortland, A. J., Freestone, I. C., and Rehren, T. (eds.), 2009. *From Mine to Microscope: Advances in the Study of Ancient Technology*. Oxford: Oxbow.
Sinopoli, C. M., 1991. *Approaches to Archaeological Ceramics*. New York: Plenum Press.
Skibo, J. M., 1992. *Pottery Function: A Use-Alteration Perspective*. New York: Plenum Press.
Skibo, J. M., 2013. *Understanding Pottery Function*. New York: Springer. Manuals in Archaeological Method, Theory and Technique.

Speakman, R. J., and Neff, H. (eds.), 2005. *Laser Ablation ICP-MS in Archaeological Research*. Albuquerque: University of New Mexico Press.

Taylor, R. E., and Aitken, M. J. (eds.), 1997. *Chronometric Dating in Archaeology*. New York: Plenum Press. Advances in Archaeological and Museum Science, 2.

Tite, M. S., 1999. Pottery production, distribution, and consumption: the contribution of the physical sciences. *Journal of Archaeological Method and Theory*, **6**(3), 181–233.

Tite, M. S., and Shortland, A. J., 2008. *Production Technology of Faience and Related Early Vitreous Materials*. Oxford: Oxford University School of Archaeology.

Tyers, P., 2012. *POTSHERD: Atlas of Roman Pottery*, http://potsherd.net and http://potsherd.net/atlas/potsherd.html (Roman period in Britain and western Europe, 1st cent. BC–5th cent. AD).

Vandiver, P. B., 2005. Craft knowledge as an intangible cultural property: a case study of Samarkand tiles and traditional potters in Uzbekistan. In Mass, J., Merkel, J., Murray, A., and Vandiver, P. B. (eds.), *Materials Issues in Art and Archaeology VII*. Pittsburgh: Materials Research Society. MRS Symposium Proceedings, 852, pp. 331–352.

Vandiver, P. B., Soffer, O., Klima, B., and Svoboda, J., 1989. The origins of ceramic technology at Dolni Věstonice, Czechoslovakia. *Science*, **246**(4933), 1002–1008.

Velde, B., and Druc, I. C., 1999. *Archaeological Ceramic Materials: Origin and Utilization*. Berlin: Springer. Natural Science in Archaeology Series.

Verhoeven, G., 2011. Taking computer vision aloft – archaeological three-dimensional reconstructions from aerial photographs with Photoscan. *Archaeological Prospection*, **18**(1), 67–73.

Waters, M. R., 1996. *Principles of Geoarchaeology: A North American Perspective*. Tucson: University of Arizona Press.

Webb, E. K., and Wachowiak, M., 2011. *Flexible Solutions for Reflectance Transformation Imaging (RTI)*. Washington, DC: Smithsonian Museum Conservation Institute. Imaging Studio Technical Note.

Wilson, M. A., Carter, M. A., Hall, C., Hoff, W. D., Ince, C., Savage, S. D., McKay, B., and Betts, I. M., 2009. Dating fired-clay ceramics using long-term power law rehydroxylation kinetics. *Proceedings of the Royal Society A*, **465**(2108), 2407–2415, doi:10.1098/rspa.2009.0117.

Wilson, M. A., Clelland, S., Carter, M. A., Ince, C., Hall, C., Hamilton, A., and Batt, C. M., 2014. Rehydroxylation of fired-clay ceramics: factors affecting early-stage mass gain in dating experiments. *Archaeometry*, **56**(4), 689–702.

Wu, X., Zhang, C., Goldberg, P., Cohen, D., Pan, Y., Arpin, T., and Bar-Yosef, O., 2012. Early pottery at 20,000 years ago in Xianrendong Cave, China. *Science*, **336**(6089), 1696–1700.

Cross-references

Archaeomineralogy
Dolní Věstonice, Pavlov, Milovice
Electron Probe Microanalyzer
Electron Spin Resonance (ESR) in Archaeological Context
Ethnogeoarchaeology
Geochemical Sourcing
Gesher Benot Ya'aqov
Grain Size Analysis
Inductively Coupled Plasma-Mass Spectrometry (ICP-MS)
Luminescence Dating of Pottery and Bricks
Organic Residues
Petrography
Radiocarbon Dating
Raman
Scanning Electron Microscopy (SEM)
X-ray Diffraction (XRD)
X-ray Fluorescence (XRF) Spectrometry in Geoarchaeology

CERÉN

Payson Sheets
Department of Anthropology, University of Colorado, Boulder, CO, USA

The Cerén archaeological site, sometimes called "Joya de Cerén" in Spanish, was a small Maya village in what is now El Salvador (Sheets, 2006). It was founded by immigrants from the north as part of the recovery from the cataclysmic disaster of the Ilopango volcanic eruption (Dull et al., 2001) that probably occurred in AD 536 (Dull et al., 2010). The immigrants settled on the bank of the Rio Sucio and began farming maize, beans, squash, chiles (Lentz et al., 1996), and manioc (Sheets et al., 2007). About 200 people lived there until a nearby volcanic vent erupted – the Loma Caldera event of ca. AD 660 – and buried it deeply under layers of volcanic ash.

Four households have been at least partially excavated, and each household built three separate structures: a domicile for sleeping and daytime activities, a storehouse (Figure 1), and a kitchen (Sheets, 2006), all built of wattle-and-daub, a highly earthquake-resistant architecture. Each household possessed about 70 complete pottery vessels (Beaudry-Corbett, 2002) and, in order to be agriculturally self-sufficient, grew food in gardens, in corn-bean fields located around the

Cerén, Figure 1 The "bodega" structure at the buried village of Cerén, occupied by Maya after the Ilopango volcanic eruption of ca. AD 536. The building was the storehouse for a family, where pottery vessels, food, clothing, grinding stones, and knives of obsidian were kept. The village was buried by volcanic ash from the nearby Loma Caldera volcanic vent, ca. AD 660, during which alternating layers of white fine-grained and dark coarse ash were deposited. The fine-grained layers were created by steam explosions when the erupting magma came into contact with river water. The steam explosions were violent enough to blast away the water, resulting in a subsequent dry phase that allowed the coarse layers to fall through the air as lapilli and volcanic bombs.

households (Sheets and Woodward, 2002), and in abundant manioc planting beds on sloping terrain outside the village. Each household had a part-time specialization and exchanged what it produced with other households. Such traded items included grinding stones (manos, metates, and perforated mortars), painted gourds, agave plants for fiber to make twine and rope, chilies, and canes to reinforce the walls of their buildings. Each household building had an incense burner to produce copal smoke for communicating with the supernatural domain (Sheets, 2006).

A civic center was established in the center of the village (Gerstle, 2002) consisting of a large plaza with special buildings facing it. In contrast to the household structures, these public buildings were constructed of massive, solid earthen walls. One building suggests an authority function, with two large benches in its front room, probably seats of power for the village elders to make decisions and adjudicate disputes. Another has been only partially excavated, and it is filled with artifacts, including a turtle shell drum. Two others have been detected only with geophysical instruments and await verification and excavation.

A functional-religious building, a sauna, was maintained by Household 2. It was used for physical and spiritual cleansing and curing respiratory ailments (Sheets, 2006).

Two overtly religious buildings were sited at the highest elevation in the area, overlooking the river (Sheets, 2006). Each had multiple floor levels, from the secular outside to the highest innermost room, and each had complex floor and wall plans with white and red painted walls. One was for village ceremonies; a harvest ritual was underway when the volcano erupted. The ritual focused on deer ceremonialism, a powerful symbol of the fertility of nature for the Maya. The other building was erected for a shaman/diviner, who kept collections of minerals and beans inside to help predict the future. As all the gender-associated artifacts left to pay for services rendered were used primarily by women, it appears the diviner was female. People would approach the structure, communicate with her through a lattice window, leave an offering, and proceed to the back to hear the result through another lattice window.

Cerén is a World Heritage site, maintained by UNESCO, the United Nations Educational, Scientific, and Cultural Organization.

Bibliography

Beaudry-Corbett, M., 2002. Ceramics and their use at Ceren. In Sheets, P. D. (ed.), *Before the Volcano Erupted: The Ancient Cerén Village in Central America*. Austin: University of Texas Press, pp. 117–138.

Dull, R. A., Southon, J. R., and Sheets, P., 2001. Volcanism, ecology, and culture: a reassessment of the Volcán Ilopango TBJ eruption in the southern Maya realm. *Latin American Antiquity*, **12**(1), 25–44.

Dull, R., Southon, J., Kutterolf, S., Freundt, A., Wahl, D., and Sheets, P., 2010. *Did the Ilopango TBJ Eruption Cause the AD 536 Event?* American Geophysical Union conference, San Francisco, December 13–17, AGU Fall Meeting Abstracts 13: p. 2370. http://www.fundar.org.sv/referencias/dull_et_al_2010_AGU.pdf

Gerstle, A. I., 2002. The civic complex. In Sheets, P. D. (ed.), *Before the Volcano Erupted: The Ancient Cerén Village in Central America*. Austin: University of Texas Press, pp. 83–88.

Lentz, D. L., Beaudry-Corbett, M. P., Reyna de Aguilar, M. L., and Kaplan, L., 1996. Foodstuffs, forests, fields, and shelter: a paleoethnobotanical analysis of vessel contents from the Ceren site, El Salvador. *Latin American Antiquity*, **7**(3), 247–262.

Sheets, P. D., 2006. *The Ceren Site: An Ancient Village Buried by Volcanic Ash in Central America*, 2nd edn. Belmont, CA: Thomson Higher Education.

Sheets, P., and Woodward, M., 2002. Cultivating biodiversity: Milpas, gardens, and the Classic Period landscape. In Sheets, P. D. (ed.), *Before the Volcano Erupted: The Ancient Cerén Village in Central America*. Austin: University of Texas Press, pp. 184–191.

Sheets, P., Dixon, C., Blanford, A., and Guerra, M., 2007. Descubrimientos e investigaciones geofísicas e arqueológicas al sur de Joya de Cerén. *El Salvador Investiga*, **3**(6), 20–26.

CHEMICAL ALTERATION

Panagiotis Karkanas
Ephoreia of Palaeoanthropology & Speleology of Southern Greece, Athens, Greece

Definitions

Authigenic minerals: Minerals forming in situ within sediments.

Chemical equilibrium: The state of a chemical reaction where the concentration of reactants and products is constant.

Cementation: Formation of new minerals that fill the pore spaces within a sediment.

Diagenesis: All of the processes that act to modify sediments after deposition.

Dissolution: Removal in solution of all or part of previously existing mineral.

Oxidation-reduction (redox): All reactions that involve changes in the oxidation number. Some oxidation reactions can be described as the combination of a substance with oxygen.

pH: A measure of the acidity or basicity of an aqueous solution. The mathematical definition of this is the negative decimal logarithm of the concentration of the hydronium cation (H_3O^+) in a solution.

Recrystallization: Change in size or shape of a crystal of a given mineral with no change in its chemical composition or mineralogy.

Saturation: The point at which a solution of a substance can dissolve no more of that substance.

Solubility: The maximum amount of a substance that can dissolve in a solvent.

Introduction

Archaeological sediments are modified after their deposition, and this has potentially serious implications for interpreting the archaeological record. Physical diagenetic modifications such as those of faunal activity (bioturbation) and compaction tend to change the original position of archaeological finds; however, chemical diagenetic modifications are major agents of alteration and destruction, yet they are often less obvious to the naked eye.

All natural environments have particular preservation characteristics. Factors such as climate, activities of organisms, and geomorphic processes play primary roles in regulating these conditions (Retallack, 2001), including the chemical nature of a burial context, which can affect the degree and bias of preservation for many objects contained within a deposit. Environmental changes are directly or indirectly related to human biological and cultural evolution, and thus, chemical alteration in natural sediments and soils is also of major importance for archaeology.

Chemical reactions at normal temperatures are basically simple; the main chemical processes involve solution, hydration, acid attack, and oxidation. In nature, practically all reactions take place simultaneously, and they tend to change the composition of the archaeological deposits, eventually moving incompatible assemblages of materials toward conditions of chemical equilibrium with the burial environment that are more adjusted to the conditions that prevailed in the sediment postdepositionally. Unfortunately, materials of direct archaeological interest can be altered or even completely dissolved. This is particularly important, for it can obscure the critical determination of whether or not the distributions of recovered archaeological materials – such as bones, teeth, plant phytoliths, charcoal, and ash – reflect their original burial distributions or new configurations and forms that came to be as a result of secondary diagenetic processes. Furthermore, chemical reactions in archaeological deposits produce alterations that may distort the original stratigraphic context. They produce volume changes, assimilate layers or create secondary layering, destroy interfaces, and change the original locations of artifacts and the relationships between artifacts. Identifying these processes is crucial if one is to interpret the recorded contexts of human activities within the precise radiometric time scale.

Method strategy

Studying chemical alteration in archaeological sites is not an easy task. It starts in the field with careful observations and stratigraphic analysis and ends in the laboratory where a set of instrumental techniques are employed (XRD, FTIR and micro-FTIR, SEM, EDS, etc.). A detailed description of these methods can be found in the relevant entries of this volume. Different types of sampling are necessary, including point and bulk sampling and removal of intact blocks of sediment for micromorphological analysis (see review in Courty et al., 1989). In most cases, a combination of techniques is used because it is impossible to control simultaneously the context of alteration features at all scales while precisely describing the chemistry of these alterations. Micromorphological analysis is used to define the relation between the different mineralogical features at the microscopic scale. At the same time, instrumental mineralogical techniques are employed to describe the mineralogy and chemistry of the defined features. Nevertheless, the base strategy of all analyses should be to understand the spatial relationships of features covering all scales of observation. This is mainly based on the sequence of disappearance and/or appearance of certain minerals and features in space as crossing alteration zones (Karkanas, 2010). This is the only way to record the sequence of events, define what is missing and what is introduced, and therefore assess the preservation conditions (see discussion below).

Agents of chemical alteration

A fundamental precondition of chemical reactions is the presence of water and/or free oxygen. This is because a fluid medium is needed for transport and exchange of chemical compounds. For example, it would be meaningless to define the acidity or alkalinity (pH) of a material in the absence of water. Free oxygen is important in the decay of all materials containing oxidizable materials, such as iron and organic matter. However, at the surface temperatures of the Earth, oxidation reactions are very slow in the absence of water. The role of water is largely that of a catalyst because it provides a favorable environment for the oxidation reaction to proceed (Krauskopf, 1979, 85). Water is equally important in biochemical reactions because all organisms that degrade organic matter need some water, even as a vapor phase, for their survival (cf. Weiner, 2010, 51). Water that is in contact with sediments carries various amounts of dissolved or particulate material that initiate chemical reactions. The chemical composition of water changes after reaction with the sediment, and therefore, static pore water very quickly attains equilibrium with the sediment; then, it becomes inactive, and no further reaction takes place until the water in the pore space is replaced by new water that has the capability of again reacting with the sediment. It follows that the amount and flow rate of water into sediment pores dictate the rate of chemical reactions. Consequently, highly altered sediment implies that substantial amounts of water have passed through its pore spaces. Note that clay sediments absorb large quantities of water but do not allow the water to pass through, mainly because their pores are not interconnected. It is thus expected that materials of archaeological interest will be better preserved in clay-rich sediment (e.g., Weiner and Bar-Yosef, 1990).

Temperature is also an important factor in speeding up reactions. An increase in temperature of 10 °C can double or triple the reaction rate (Krauskopf, 1979, 8). Therefore, in warm climates, weathering and consequential chemical alteration proceed faster in the presence of water. Hence, soil profiles in areas with tropical climates show deep chemical alteration (Nahon, 1991).

Carbon dioxide readily dissolves in water producing carbonic acid, and the increased acidity of this water makes it a better solvent. All natural waters exposed to air become dilute solutions of carbonic acid, and in the absence of other acid sources, the pH of rainwater is about 5.7. Other dissolved components, such as nitrogen and sulfur, also increase the acidity of water. The significance of these acids is only locally important, however, and in most cases, the acidity of water is due to elevated concentrations of CO_2 released by the decay of organic matter. In the presence of oxygen, soil organisms oxidize organic matter and convert it into carbon dioxide, water, organic acids, and other compounds. Again, an important factor in determining the rate of oxidation of organic matter is the extent of water flow that replenishes oxygen. In the absence of oxygen, anaerobic processes result in the formation of other acidic products (Weiner, 2010).

In summary, the fluid medium and its capacity of reacting with the sediment are what makes reactions proceed beneath the earth's surface. Although this is quite apparent, we tend to forget its implications. The mere existence of an alteration implies some kind of reaction with a fluid possessing certain characteristics, and this information alone already determines something about past environmental conditions.

Major chemical diagenetic processes

The most important chemical processes affecting archaeological deposits are also simple; they include dissolution, recrystallization, authigenesis, cementation, and oxidation.

Dissolution

Dissolution occurs when the solubility of a particular mineral is exceeded under a given set of environmental conditions that are normally defined by pH, oxidation conditions, temperature, and the amount of soluble salts. The stability of the most important carbonate minerals (calcite, aragonite) increases with decreasing temperature. However, the most decisive agent of dissolution of carbonate minerals is pH. Calcite ($CaCO_3$) is stable at pH values above about 8, but it undergoes solution under acidic conditions. Therefore, carbonate materials of archaeological importance, such as calcareous shells, are not stable under acidic conditions.

An important but generally neglected carbonate component of archaeological sites is calcitic ash. During combustion of wood, CaO oxide is formed from the oxidation of calcium oxalate crystals that are commonly found in wood. Upon cooling, the CaO will absorb CO_2 from the atmosphere and react to form $CaCO_3$ in the form of calcite. Due to its fine texture and high porosity, ash readily reacts with acidic rainwater or humic acids in some soils and dissolves. It is obvious that decalcified sediments would not preserve ash or any other calcareous material of archaeological interest; however, if the groundwater equilibrates in calcareous environments, it will become alkaline with a pH close to 8.2, and as a result, further dissolution of calcite will be prevented. This is known as the buffer capacity of calcite. It follows that wood ash will be preserved in sites where calcite is found in large quantities, such as in a limestone (e.g., karstic) environment. Furthermore, in sites possessing large amounts of calcitic ash, the pH of the groundwater will be buffered by the ash even if it is relatively acidic; in this way, much of the archaeologically deposited ash will be preserved (see Weiner, 2010, 77). Of course, this will be dictated by the rate of ash input and generally the sedimentation rate in relation to the rate of water flow (see above). As already stated, degradation of organic matter can also produce acidity, which can reduce the pH of the groundwater leading to ash dissolution. Another environment where ash is often preserved is caves. Caves are formed mainly in carbonate rocks (limestone and dolomite), and therefore, waters flowing within their environment are usually alkaline. Impressive well-preserved ashy sequences are known from several Paleolithic caves, e.g., Kebara Cave (Goldberg et al., 2007).

Dung spherulites are another form of calcium carbonate found in archaeological sites that contain stabling remains. They appear to be formed in the ruminants' gut and consist of microscopic radial masses forming an approximately spherical aggregate (Canti, 1997). They also survive burning and are often found in large quantities in ashed dung. It has been shown experimentally that dung spherulites do not survive in sediments with a pH lower than approximately 7.7 and that they are more soluble than geogenic calcite (Canti, 1999), something that has been also observed in archaeological sediments (e.g., Albert et al., 2008). Conditions of preservation affecting dung spherulites are broadly similar to those of wood ash.

Bone is another material of archaeological interest that can dissolve. The mineral component of bone is a biogenic variant of the phosphate mineral apatite. Berna et al. (2004) were able to show experimentally that bone is stable in sediments with pH above 8.1. In more acidic environments and particularly at pH values below 7, bone will rapidly dissolve depending on the water flow (Hedges and Millard, 1995). Berna et al. (2004) also confirmed that, in the presence of calcite, bone is stable due to the buffering capacity of a calcitic environment – a process that is predictable based on the discussion above and demonstrated already in case studies (Weiner et al., 1993).

Phytoliths are a biogenic form of opal and another primary material of archaeological interest. They are produced by many plants as a siliceous packing deposited within varied anatomical components using hydrous silica taken up through the roots. These mineralized parts of plants are considered relatively stable in most sedimentary environments, and they survive burning or oxidation well. However, opal is a hydrous, amorphous silica polymorph and has a constant solubility of up to 8.5 pH; solubility increases rapidly above pH 9 (Krauskopf, 1979). Therefore, dissolution of phytoliths to fluctuating degrees can be assumed if calcite is present, calcite being an indicator of a generally alkaline environment (Piperno, 1988). Nonetheless, the solubility of amorphous silica and phytoliths is almost an order of magnitude higher than that of the most stable silicate mineral, quartz (Fraysse et al., 2009). As a consequence, the solubility of phytoliths is high enough that they can dissolve in the normal pH range (4–8) of the soil environment, assuming a high rate of water flow through the sediment (Fraysse et al., 2009).

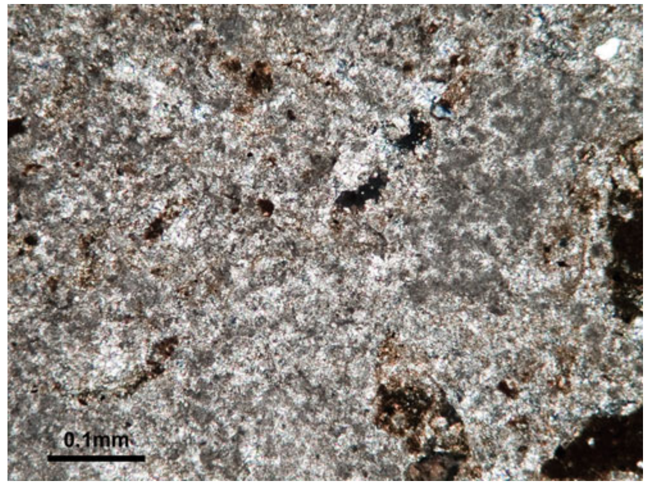
Silica artifacts such as chert and flint are usually composed of micro-quartz with variable amounts of other silica minerals, mainly chalcedony and opal (Luedtke, 1992). Quartz is practically non-soluble below pH 9, but opal and the structurally disordered chalcedony are much more soluble than quartz (Krauskopf, 1979; Sheppard and Pavlish, 1992; Burroni et al., 2002). Therefore, the silica mineral composition of artifacts will determine the dissolution rate, which also depends on the amount of water flow through the sediment. Silica artifacts usually contain mineral impurities that possess different solubilities. In particular, calcite is a frequent minor constituent of chert artifacts. Therefore, dissolution of artifacts is expected to vary not only under different pH regimes but also according to local raw materials (cf. Sheppard and Pavlish, 1992; Burroni et al., 2002). For example, calcite inclusions may dissolve or transform to phosphate minerals (see below).

As already stated in the description of the agents of chemical alteration, it appears that, given sufficient time, the dissolution of several materials of archaeological importance is largely dictated by the amount and flow rate of water. Therefore, not just climatic conditions but also localized hydrological configurations determine the fate of many archaeological materials.

Recrystallization

Recrystallization implies a change from a more soluble to a less soluble substance. Usually, small crystals recrystallize into bigger crystals. Recrystallization is very important in carbonate sediments. In particular, calcitic ash crystals due to their very small size are readily recrystallized to form indurated sediments that resemble natural carbonate rocks (Karkanas et al., 2007). However, the presence of pseudomorphs of the calcium oxalate crystals associated with charcoal or fine charred material can differentiate recrystallized ash from natural geogenic calcite (Figure 1). Furthermore, charcoal, oxidized (burnt) soil aggregates, as well as a close association with burnt bone and other burnt archaeological materials are further indications.

Bone can also recrystallize. After death, crystals of bone mineral continue to grow and increase their size and order. Berna et al. (2004) showed experimentally that buried bone in deposits between pH 8.1 and 7.4 will undergo recrystallization and be replaced by more stable



Chemical Alteration, Figure 1 Photomicrograph of light gray sparitic calcite replacing dark gray micritic aggregates in a sample from Qesem Cave, Israel. Some of the micritic aggregates reveal the remnant rhombic shapes of the original ash crystals (especially in the *upper right* quarter of the image). *PPL* plane polarized light.

forms of apatite. This is a significant observation because it shows that bone becomes more stable with time and that it attains greater stability when authigenic apatite is forming in the sediments (see below).

Authigenesis and cementation

Precipitation of new minerals into pore spaces results in cementation of the sediment and production of an indurated deposit that will eventually become rock. Cementation differs from recrystallization in that it refers to the formation of new minerals (authigenesis) inside the sediment. Each mineral forms under a specific set of conditions, and hence, its presence is indicative of the conditions that prevailed at the time of formation. Thus, the formation of an authigenic mineral can be regarded as the product resulting from changes in specific environmental parameters. These parameters define the stability field of the authigenic mineral under consideration.

Waters that are saturated with bicarbonate will precipitate calcite with the release of carbonate gas and water, but different forms will result depending on the mechanism of precipitation and the local environmental conditions. Direct evaporation will bring about saturation of the solution and precipitation when the solubility is exceeded. Release of carbonate gas (degassing) will also lead to supersaturation and precipitation of calcite, and this process is more common in the formation of cave speleothems. Percolating waters rich in carbon dioxide deriving from the soil enter the cave interior through fissures in the rock. These waters will equilibrate with the new cave environment, which is relatively depleted in carbon dioxide; under such conditions, carbon dioxide will be lost from solution through degassing, and dissolved carbonate will precipitate as a solid mineral (Gillieson, 1996, 116–120). Dripping, seeping, or flowing water on the surface of caves produces a variety of forms known as stalactites, stalagmites, flowstones, and others named according to their morphologies (Hill and Forti, 1997). Due to their incremental development, speleothems are proving to be the best records of the history of climate in an area. The isotopic analysis of oxygen and carbon in the calcite of each lamina or ring reveals the chemistry of waters that precipitated it, and this in turn reveals something about the climatic and local environmental conditions that produced these waters (Ford, 1997). The same waters percolating within the cave sediment will also precipitate calcite, thereby cementing the sediments and producing a hard rock known as cave breccia. Often, cave breccias seal and preserve bones dating to millions of years ago, like the famous caves within the Cradle of Humankind in South Africa, where important early hominin fossils have been found (e.g., Pickering and Kramer, 2010).

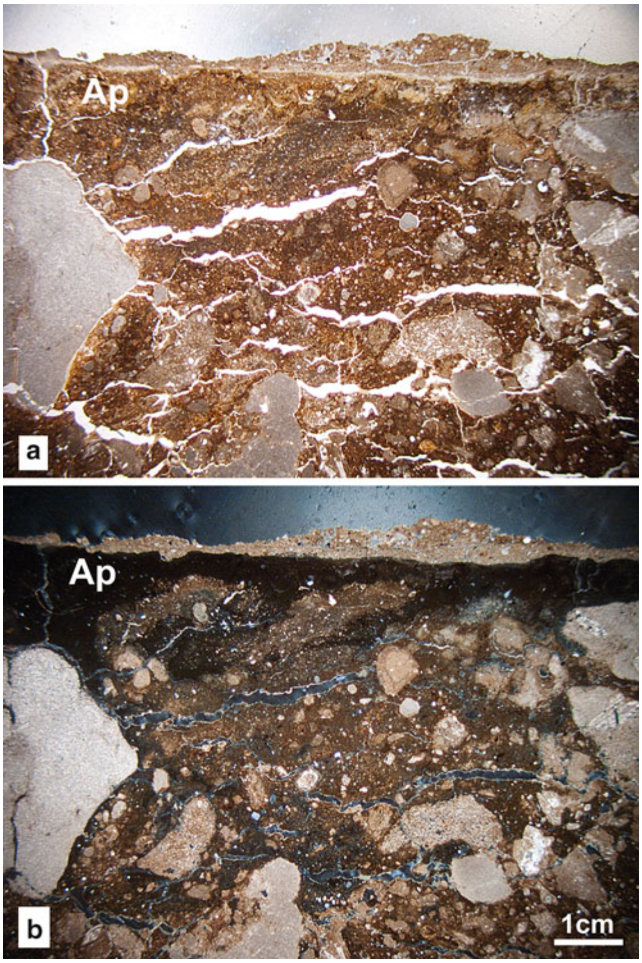
In soil environments, biological activity is an additional factor that controls the precipitation of carbonates. Root evapotranspiration is another mechanism that removes water from solution. Evapotranspiration is considered to be a major cause of rhizocretion (calcified root) formation (Wright and Tucker, 1991). Organic processes regulate the carbon dioxide budget in soils but also induce carbonate precipitation by direct uptake of CO_2 or other mechanisms that trigger its precipitation. Nevertheless, evaporation, evapotranspiration, and probably degassing are climatically controlled, and numerous studies suggest that calcareous soils are formed in arid to subhumid environments (e.g., Zhou and Chafetz, 2009). The isotopic profiles of calcitic nodules that formed in well-developed calcareous soils (calcrete or caliche) have also been used to reconstruct ancient environments. The carbon isotopic composition of pedogenic carbonate is related to the soil CO_2, which in turn is correlated with the proportion of plants employing C3 and C4 photosynthetic pathways. The carbon isotopic composition of plants reflects the climate and the environment in which they grow and is, therefore, a powerful tool in paleoecological reconstruction. This information has been used to estimate rates of erosion, alluviation, and archaeological site preservation potentials (Nordt, 2001) as well as explain the context of human subsistence and evolution, (e.g., Cerling et al., 2011).

Authigenic gypsum is frequently reported in archaeological sites. It is related to the degradation of organic matter (Shahack-Gross et al., 2004; Cabanes and Albert, 2011) and is also found in areas with stabling remains and dry conditions (Figure 2). In the initial stages of degradation, sulfate accumulates due to microbial activity. Increased acidity and sulfate concentration favor the formation of gypsum at the expense of calcite (Donner and Lynn, 1989). An interesting observation is the hydration of anhydrite ash ($CaSO_4$) to produce gypsum ($CaSO_4 \cdot 2H_2O$). Anhydrite is formed during the burning of gypsum-bearing plants such as tamarisk (Shahack-Gross and Finkelstein, 2008).

Chemical Alteration, Figure 2 Banded concentration of gypsum nodules (indicated by an *arrow*) in the historical deposits of Drakaina Rockshelter, Greece. The association of gypsum with dung spherulites identified microscopically suggests that the cave was used as a pen.

Formation of gypsum in soil environments is also favored by the presence of organic matter at high pH (Poch et al., 2010, and references therein). However, most soil gypsum formations are found in well-drained soils under dry conditions. Soil parent material and aeolian dust are the most important factors in gypsum distribution. Gypsum is more soluble than the carbonates, and therefore, gypsic horizons normally do not coexist with calcic horizons (Amit et al., 2011). When gypsum is found in calcrete profiles, its distribution is a useful guide to soil hydrology and precipitation (<250 mm/year).

Degradation of organic matter also releases chemical compounds such as phosphates. In all occupational sites, anthropogenic inputs of human waste and organic residues add phosphates to the sediment in the form of animal stabling, manuring, fertilizing, and privy accumulations (Goldberg and Macphail, 2006; Karkanas and Goldberg, 2010). The major source of phosphate, however, is not directly the original vegetal remains but their reprocessed, phosphate-rich contributions derived from animal excrements (e.g., horses, cattle, goats, and sheep; see, e.g., Macphail et al., 2004). Human activities related to preparation of animal food or processed foods such as oil and fat are probably additional contributors after their degradation (Figure 3). As phosphate is relatively insoluble, it tends to remain in the area where it was originally deposited. Depending on the pH and the availability of other chemical elements, a variety of authigenic phosphate minerals can be formed. In alkaline environments and in the presence of calcium, the calcium phosphate mineral apatite is formed; bone mineral is a variant of the same mineral. In more acidic environments, i.e., at a pH below



Chemical Alteration, Figure 3 Photomicrograph of apatite (*Ap*) (confirmed by FTIR: Karkanas and Stratouli, 2008) altering the surface of a lime floor in a sample from Drakaina Rockshelter, Greece. In PPL (**a**), apatite is *yellowish*. In XPL, or crossed polarized light (**b**), apatite shows optically isotropic behavior and becomes *dark*, blocking transmitted light.

ca. 7, apatite is transformed into a series of complex aluminum-rich phosphate minerals (Karkanas et al., 2000). Obviously, bone is not stable in such environments. Authigenic phosphates can be formed in large amounts and eventually cement the sediment (Figure 4). This has often been observed in caves where the existence of substantial deposits of bat guano provides the necessary phosphorus for the reactions to take place (Shahack-Gross et al., 2004).

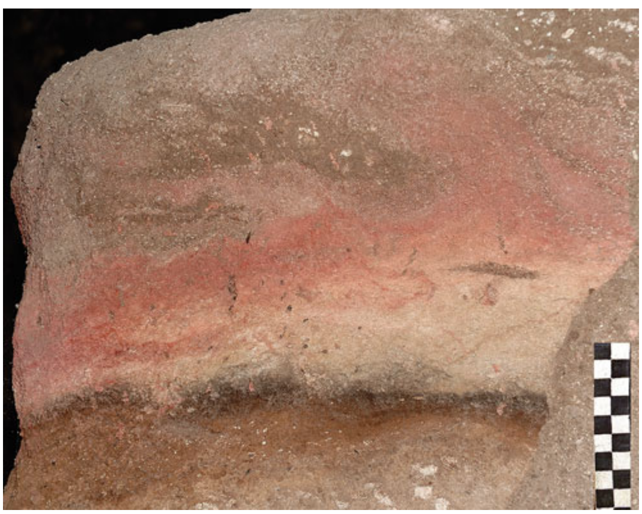
In the presence of phosphorus, calcareous materials are not stable and are readily transformed to phosphates. The reaction is one of dissolution and precipitation; hence, a new mineral is formed. Authigenic apatite can replace calcitic ash and calcareous shells, and it can alter limestone to the point where it is no longer recognizable. Phosphate-rich solutions from the degradation of food products have also been reported to alter lime floors and form apatite alteration surfaces (Figure 3) (Karkanas and Stratouli, 2008; Regev et al., 2010). In the case of ash, the general structure of the burnt layer, i.e., ashes overlying an organic/charcoal-rich or fire-reddened substrate, can still be recognized after alteration to apatite. As phosphate reactions proceed, these apatite formations are also transformed to aluminum-rich phosphates.

Oxidation

Among the products of chemical alteration, iron oxides are the most conspicuous because of their bright colors. Iron oxides that formed in contact with air are in an oxidative state (ferric iron). The color of the simple oxides, such as hematite, is red and that of the hydrates, such as goethite, is yellow to brown. Iron-rich minerals in a reduced state (ferrous iron), such as siderite, have a gray color, and a variety of authigenic ferrous iron-rich clays show green and gray colors. Indeed, the rank of hues in the Munsell soil color chart follows this trend. That is, colors in reducing waterlogged environments are bluish or greenish to olive yellow (hues of PB, BG, G, GY, and 10Y–5Y); aerated, slightly oxidized sediments are yellowish to reddish brown (hues of 2.5Y–2.5YR); and fully oxidized sediments are red (hue of R). Oxidation reactions are mainly observed in well-drained soils and in warm climates with contrasting wet and dry seasons (Courty et al., 1989, 165–167). Therefore, iron-containing authigenic minerals can, in principle, be used to reconstruct past oxidation conditions. It is important to note here that reddening can be produced by high temperatures associated with human activities such as fireplaces and other pyrotechnological processes; however, it has been observed that that fire reddening always affects the substrate of the burning feature and that certain microscopic features differentiate it from pedological processes (see Courty et al., 1989, 169).

Many of the primary constituents of the sediments that are most important archaeologically consist of organic matter (pollen, charcoal, and other botanical remains), and they may be destroyed under oxidizing conditions. The oxidation of organic matter produces reducing conditions because oxygen is consumed by the reaction. Iron oxides are very insoluble under oxidation conditions, but when very little or no oxygen is present, they will readily dissolve. Dissolved reduced iron will diffuse away until it encounters oxygen. It will then reoxidize, and in so doing, it will again become insoluble and precipitate as ferric iron oxides such as hematite (Figure 5). Thus, an observation that iron oxide minerals have been redistributed is an indication of past reducing conditions. This, in turn, can be used to suggest that organic matter was initially present but it decayed postdepositionally. Oxidation over long periods of time has been found to affect buried charcoal, and this has serious implications for radiocarbon dating (Cohen-Ofri et al., 2006).

Chemical Alteration, Figure 4 Phosphate cementing fissures (*white-filled crevices*) produced by freeze-thaw activity in Theopetra Cave, Greece.



Chemical Alteration, Figure 5 Bright red, hematite-rich sediments above oxidized burnt remains from Theopetra Cave, Greece.

Similar conditions have been observed for the precipitation of manganese oxides in archaeological sites (Marín Arroyo et al., 2008). Manganese is released during the decomposition of organic matter accumulated by anthropogenic activities. Then, pH increase leads to manganese precipitation in insoluble oxidative forms. Black coloring and encrustations on bones are often the result of this process (Shahack-Gross et al., 1997).

The oxidation conditions of sediments favor the formation of several other iron-rich minerals as well. In waterlogged sediments, vivianite, an iron-rich phosphate mineral, is formed under reducing conditions. These occurrences have been related to the degrading of human and animal waste (Bertran and Raynal, 1991; Gebhardt and Langohr, 1999; McGowan and Prangnell, 2006).

Apparently, oxidation and reduction reactions in archaeological sites are directly related to the breakdown of organic matter, and since most anthropogenic activities result in the accumulation of organic matter, minerals that are favored by these conditions will be preferably formed.

Broader archaeological implications

As discussed above, the study of chemical alterations in geoarchaeological contexts can provide valuable information for paleoenvironmental reconstruction and for assessing the integrity of the archaeological record. Knowing the mineral that was replaced as well as the mineral that replaced it allows us also to reconstruct the trends in changing paleoenvironmental conditions. This, in turn, can be used to determine whether the archaeological materials of interest were likely to have been stable under such assumed preexisting conditions – providing that we know the nature of their stability (how they react) under these conditions. Retallack (2001) has constructed a diagram with the theoretical Eh-pH stability fields of common kinds of terrestrial fossils preserved in paleosols. For example, based on phosphate mineral stabilities, we can predict when bone mineral can be expected to be preserved in the archaeological record. As already discussed above, the formation of authigenic apatite in sediments is not accompanied by bone dissolution. Therefore, the phosphate source of newly formed apatite cannot be the bones themselves. Bone will be unstable in a chemical environment in which the mineral apatite is not stable. Accordingly, an indication of the instability of apatite will

Chemical Alteration, Figure 6 Dissolution of ash in a pit at the Kolona Bronze Age site, Aegina Island, Greece, has resulted in considerable subsidence and disruption of the continuation of the burnt layer that was covering the pit. *White pins* mark the burnt layer and its original surface at the *left*, *red pins* mark the outline of the pit, and *yellow pins* mark the burnt layer covering the pit where it now lies approximately 20 cm below its former level.

be the presence within sediments of aluminum-rich phosphate minerals, which are more stable than apatite (Karkanas et al., 2000; Karkanas, 2010).

Chemical reactions also involve changes in volume. During the transformation of one mineral type to another, volume can increase or decrease depending upon the specific transformation. The more important volume change is, however, due to loss of material during the dissolution stage. This is most pronounced in the case of wood ash (Figure 6), which on average contains about 98 vol.% calcite, which is soluble in normal rainwater. If all the calcite is lost, the volume decrease could be 50 times (Karkanas et al., 2000). However, dissolution of mineral phases may not necessarily result in a volume change, but only in an increase in porosity. Volume changes due to diagenesis affect calculations of the density of bones as well as lithic and pottery artifact distributions within the archaeological deposit, a measure that is often used to assess "intensity" of occupation.

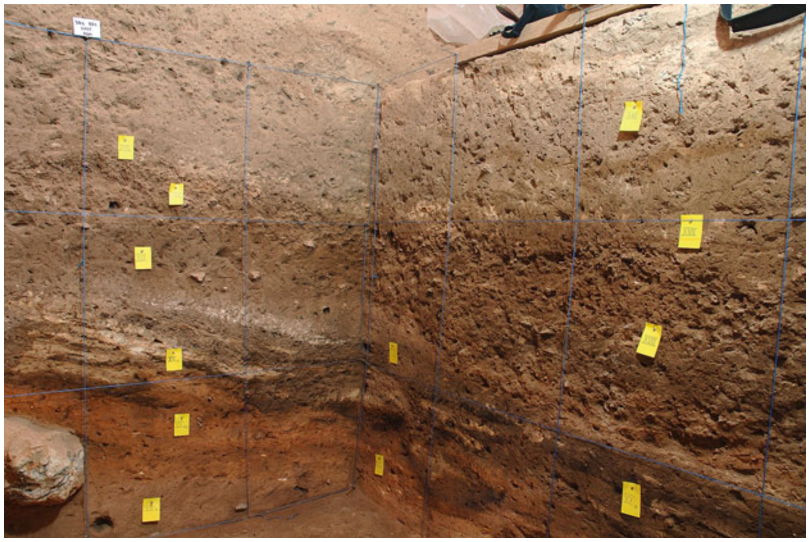
Volume changes are also accompanied by changes in the mineral assemblages. The differing assemblages, in turn, have different contents of the elements uranium, thorium, and potassium, which are the major sources of the radiation that affects dating by thermoluminescence and electron spin resonance (Mercier et al., 1995).

Chemical alteration can be also used to define major stratigraphic changes. Dissolution is not likely to be uniform over the whole sedimentary layer; thinning can occur in some areas and not in others. Therefore, differential dissolution can produce changes in the inclination of the layers. Such changes produce unconformities inside the archaeological sequence, which can translate into considerable time gaps before the new layers that are not affected by diagenesis are deposited horizontally (Figure 7). Nevertheless, even in cases where considerable volume changes are not involved or dissolution is uniform, direct contact between altered and unaltered sediments or sediments showing different chemical alterations often imply major changes in paleoenvironmental conditions (e.g., Goldberg and Berna, 2010). The reasons for this change could involve climate, occupational intensity, site abandonment, or local changes in the landscape.

Most of the impressive alteration features in archaeology have been described from cave sequences. Caves were used preferentially during prehistory, and being perfect sedimentary traps, they preserve long occupational sequences. They are also characterized by an active but confined hydrologic regime and accumulation of large amounts of organic matter, usually in the form of bat and other types of guano or dung from animals that were penned within the cave. Therefore, diagenesis is often very aggressive with obvious consequences for the preservation of archaeological materials. However, more recent and open-air sites also show alteration features, such as volume changes in tell sediments (Albert et al., 2008), authigenic phosphate minerals in medieval sites (Bertran and Raynal, 1991; Gebhardt and Langohr, 1999), and bone alteration features associated with food processing in open-air environments (Simpson et al., 2000). Unfortunately, the lack of systematic studies in such sites enhances the bias in favor of caves.

Summary

Chemical alteration affects the bulk of the sediments that contain materials of archaeological importance.



Chemical Alteration, Figure 7 Photograph of a strongly inclined altered ash layer at the *bottom* overlain by subhorizontal deposits (*left side* section) at Klissoura Cave 1, Greece.

Understanding the chemical processes responsible for these alterations will usually facilitate an assessment of the completeness of archaeological record. Materials of direct or indirect archaeological importance recrystallize or completely dissolve and oxidize, thereby seriously affecting the recoverable evidence and subsequent interpretation of past human activities. Newly formed minerals or minerals that remain stable under changing chemical conditions can be used to deduce prior states of preservation. Moreover, cementation, dissolution, and oxidation processes are environmentally controlled and therefore can be used to reconstruct ancient environments.

Bibliography

Albert, R. M., Shahack-Gross, R., Cabanes, D., Gilboa, A., Lev-Yadun, S., Portillo, M., Sharon, I., Boaretto, E., and Weiner, S., 2008. Phytolith-rich layers from the Late Bronze and Iron Ages at Tel Dor (Israel): mode of formation and archaeological significance. *Journal of Archaeological Science*, **35**(1), 57–75.

Amit, R., Simhai, O., Ayalon, A., Enzel, Y., Matmon, A., Crouvi, O., Porat, N., and McDonald, E., 2011. Transition from arid to hyper-arid environment in the southern Levant deserts as recorded by early Pleistocene cummulic Aridisols. *Quaternary Science Reviews*, **30**(3–4), 312–323.

Berna, F., Matthews, A., and Weiner, S., 2004. Solubilities of bone mineral from archaeological sites: the recrystallization window. *Journal of Archaeological Science*, **31**(7), 867–882.

Bertran, P., and Raynal, J.-P., 1991. Apport de la micromorphologie à l'étude archéologique du village médiéval de Saint-Victor de Massiac (Cantal). *Revue archéologique du Centre de la France*, **30**(30), 137–150.

Burroni, D., Donahue, R. E., Pollard, A. M., and Mussi, M., 2002. The surface alteration features of flint artefacts as a record of environmental processes. *Journal of Archaeological Science*, **29**(11), 1277–1287.

Cabanes, D., and Albert, R. M., 2011. Microarchaeology of a collective burial: Cova des Pas (Minorca). *Journal of Archaeological Science*, **38**(5), 1119–1126.

Canti, M. G., 1997. An investigation of microscopic calcareous spherulites from herbivore dungs. *Journal of Archaeological Science*, **24**(3), 219–231.

Canti, M. G., 1999. The production and preservation of faecal spherulites: animals, environment and taphonomy. *Journal of Archaeological Science*, **26**(3), 251–258.

Cerling, T. E., Wynn, J. G., Andanje, S. A., Bird, M. I., Korir, D. K., Levin, N. E., Mace, W., Macharia, A. N., Quade, J., and Remien, C. H., 2011. Woody cover and hominin environments in the past 6 million years. *Nature*, **476**(7358), 51–56.

Cohen-Ofri, I., Weiner, L., Boaretto, E., Mintz, G., and Weiner, S., 2006. Modern and fossil charcoal: aspects of structure and diagenesis. *Journal of Archaeological Science*, **33**(3), 428–439.

Courty, M. A., Goldberg, P., and Macphail, R., 1989. *Soils and Micromorphology in Archaeology*. Cambridge: Cambridge University Press.

Donner, H. E., and Lynn, W. C., 1989. Carbonate, halide, sulfate, and sulfide minerals. In Dixon, J. B., and Weed, S. B. (eds.), *Minerals in Soil Environments*, 2nd edn. Madison: Soil Science Society of America. SSSA Book Series, 1, pp. 279–330.

Ford, D., 1997. Dating and paleo-environmental studies of speleothems. In Hill, C. A., and Forti, P. (eds.), *Cave Minerals of the World*, 2nd edn. Huntsville: National Speleological Society, pp. 271–284.

Fraysse, F., Pokrovsky, O. S., Schott, J., and Meunier, J.-D., 2009. Surface chemistry and reactivity of plant phytoliths in aqueous solutions. *Chemical Geology*, **258**(3–4), 197–206.

Gebhardt, A., and Langohr, R., 1999. Micromorphological study of construction materials and living floors in the medieval motte of Werken (West Flanders, Belgium). *Geoarchaeology*, **14**(7), 595–620.

Gillieson, D. S., 1996. *Caves: Processes, Development, and Management*. Oxford: Blackwell.

Goldberg, P., and Berna, F., 2010. Micromorphology and context. *Quaternary International*, **214**(1–2), 56–62.

Goldberg, P., and Macphail, R. I., 2006. *Practical and Theoretical Geoarchaeology*. Malden: Blackwell.
Goldberg, P., Laville, H., Meignen, L., and Bar-Yosef, O., 2007. Stratigraphy and geoarchaeological history of Kebara Cave, Mount Carmel. In Bar-Yosef, O., and Meignen, L. (eds.), *Kebara Cave, Mt. Carmel, Israel: The Middle and Upper Paleolithic Archaeology, Part I*. Cambridge, MA: Harvard University, Peabody Museum of Archaeology and Enthnology. American School of Prehistoric Research Bulletin, 49, pp. 49–89.
Hedges, R. E. M., and Millard, A. R., 1995. Bones and groundwater: towards the modelling of diagenetic processes. *Journal of Archaeological Science*, **22**(2), 155–164.
Hill, C. A., and Forti, P., 1997. *Cave Minerals of the World*, 2nd edn. Huntsville: National Speleological Society.
Karkanas, P., 2010. Preservation of anthropogenic materials under different geochemical processes: a mineralogical approach. *Quaternary International*, **210**(1–2), 63–69.
Karkanas, P., and Goldberg, P., 2010. Phosphatic features. In Stoops, G., Marcelino, V., and Mees, F. (eds.), *Interpretation of Micromorphological Features of Soils and Regoliths*. Amsterdam: Elsevier, pp. 521–541.
Karkanas, P., and Stratouli, G., 2008. Neolithic lime plastered floors in Drakaina Cave, Kephalonia Island, Western Greece: evidence of the significance of the site. *Annual of the British School at Athens*, **103**, 27–41.
Karkanas, P., Bar-Yosef, O., Goldberg, P., and Weiner, S., 2000. Diagenesis in prehistoric caves: the use of minerals that form in situ to assess the completeness of the archaeological record. *Journal of Archaeological Science*, **27**(10), 915–929.
Karkanas, P., Shahack-Gross, R., Ayalon, A., Bar-Matthews, M., Barkai, R., Frumkin, A., Gopher, A., and Stiner, M., 2007. Evidence for habitual use of fire at the end of the Lower Paleolithic: site-formation processes at Qesem Cave, Israel. *Journal of Human Evolution*, **53**(2), 197–212.
Krauskopf, K. B., 1979. *Introduction to Geochemistry*, 2nd edn. New York: McGraw-Hill.
Luedtke, B. E., 1992. *An Archaeologist's Guide to Chert and Flint*. Los Angeles: Institute of Archaeology, University of California. Archaeological Research Tools, 7.
Macphail, R. I., Cruise, G. M., Allen, M. J., Linderholm, J., and Reynolds, P., 2004. Archaeological soil and pollen analysis of experimental floor deposits; with special reference to Butser Ancient Farm, Hampshire, UK. *Journal of Archaeological Science*, **31**(2), 175–191.
Marín Arroyo, A. B., Landete Ruiz, M. D., Vidal Bernabeu, G., Seva Román, R., Gonzáles Morales, M. R., and Straus, L. G., 2008. Archaeological implications of human-derived manganese coatings: a study of blackened bones in El Mirón Cave, Cantabrian Spain. *Journal of Archaeological Science*, **35**(3), 801–813.
McGowan, G., and Prangnell, J., 2006. The significance of vivianite in archaeological settings. *Geoarchaeology*, **21**(1), 93–111.
Mercier, N., Valladas, H., Joron, J. L., Schiegl, S., Bar-Yosef, O., and Weiner, S., 1995. Thermoluminescence dating and the problem of geochemical evolution of sediments. A case study: the Mousterian levels at Hayonim. *Israel Journal of Chemistry*, **35**(2), 137–141.
Nahon, D. B., 1991. *Introduction to the Petrology of Soils and Chemical Weathering*. New York: Wiley.
Nordt, L. C., 2001. Stable C and O isotopes in soils: applications for archaeological research. In Goldberg, P., Holliday, V. T., and Ferring, C. R. (eds.), *Earth-Sciences and Archaeology*. New York: Kluwer/Plenum Publishers, pp. 419–445.
Pickering, R., and Kramers, J. D., 2010. Re-appraisal of the stratigraphy and determination of new U-Pb dates for the Sterkfontein hominin site, South Africa. *Journal of Human Evolution*, **59**(1), 70–86.
Pickering, R., Hancox, P. J., Lee-Thorp, J. A., Grün, R., Mortimer, G. E., McCulloch, M., and Berger, L. R., 2007. Stratigraphy, U-Th chronology, and paleoenvironments at Gladysvale Cave: insights into the climatic control of South African hominin-bearing cave deposits. *Journal of Human Evolution*, **53**(5), 602–619.
Piperno, D. R., 1988. *Phytolith Analysis: An Archaeological and Geological Perspective*. San Diego: Academic.
Poch, R. M., Artieda, O., Herrero, J., and Lebedeva-Verba, M., 2010. Gypsic features in soils and sediments. In Stoops, G., Marcelino, V., and Mees, F. (eds.), *Interpretation of Micromorphological Features of Soils and Regoliths*. Amsterdam: Elsevier, pp. 195–216.
Regev, L., Zukerman, A., Hitchcock, L., Maeir, A. M., Weiner, S., and Boaretto, E., 2010. Iron age hydraulic plaster from tell Es-Safi/Gath, Israel. *Journal of Archaeological Science*, **37**(12), 3000–3009.
Retallack, G. J., 2001. *Soils of the Past. An Introduction to Paleopedology*, 2nd edn. Oxford: Blackwell Science.
Shahack-Gross, R., and Finkelstein, I., 2008. Subsistence practices in an arid environment: a geoarchaeological investigation in an Iron Age site, the Negev Highlands, Israel. *Journal of Archaeological Science*, **35**(4), 965–982.
Shahack-Gross, R., Bar-Yosef, O., and Weiner, S., 1997. Black-coloured bones in Hayonim Cave, Israel: differentiating between burning and oxide staining. *Journal of Archaeological Science*, **24**(5), 439–446.
Shahack-Gross, R., Berna, F., Karkanas, P., and Weiner, S., 2004. Bat guano and preservation of archaeological remains in cave sites. *Journal of Archaeological Science*, **31**(9), 1259–1272.
Sheppard, P. J., and Pavlish, L. A., 1992. Weathering of archaeological cherts: a case study from the Solomon Islands. *Geoarchaeology*, **7**(1), 41–53.
Simpson, I. A., Perdikaris, S., Cook, G., Campbell, J. L., and Teesdaly, W. J., 2000. Cultural sediment analyses and transitions in early fishing activity at Langenesværet, Vesterålen, Northern Norway. *Geoarchaeology*, **15**(8), 743–763.
Weiner, S., 2010. *Microarchaeology: Beyond the Visible Archaeological Record*. New York: Cambridge University Press.
Weiner, S., and Bar-Yosef, O., 1990. States of preservation of bones from prehistoric sites in the Near East: a survey. *Journal of Archaeological Science*, **17**(2), 187–196.
Weiner, S., Goldberg, P., and Bar-Yosef, O., 1993. Bone preservation in Kebara Cave, Israel using on-site fourier transform infrared spectrometry. *Journal of Archaeological Science*, **20**(6), 613–627.
Wright, V. P., and Tucker, M. E., 1991. Calcretes: an introduction. In Wright, V. P., and Tucker, M. E. (eds.), *Calcretes*. Oxford: Blackwell. International Association of Sedimentologists, Reprint Series, 2, pp. 1–22.
Zhou, J., and Chafetz, H. S., 2009. Biogenic caliches in Texas: the role of organisms and effect of climate. *Sedimentary Geology*, **222**(3–4), 207–225.

Cross-references

Anthrosols
Cave Settings
Electron Probe Microanalyzer
Fourier Transform Infrared Spectroscopy (FTIR)
Hearths and Combustion Features
Kebara Cave
Privies and Latrines
Rockshelter Settings
Scanning Electron Microscopy (SEM)
Soil Micromorphology
Speleothems
Sterkfontein/Swartkrans/Kromdraai
X-ray Diffraction (XRD)

CHRONOSTRATIGRAPHY

Daniel Richter
Department of Geography, Geographisches Institut
University of Bayreuth, Bayreuth, Germany
Department of Human Evolution, Max Planck
Institute for Evolutionary Anthropology, Leipzig,
Germany

Definition

In earth science, chronostratigraphy defines rock strata by their temporal relations, reconciling stratigraphy with relative and chronometric dating in the historical discipline of geology. Relative dating by stratigraphic correlations, employing bio-, magneto-, or isotope-stratigraphy, provides a relative time scale between specific events in the geologic record. Thus, chronostratigraphic unit definitions are based on age relations, which are referred to on a relative linear time scale and preferably fixed in time by chronometric (often wrongly termed *absolute*) dating. With some differences in scale and evidence, chronostratigraphy is also applied to cultural material left by humans.

Chronostratigraphy

In the original geological definition, the temporal sequence of rock strata in more than one *lithostratigraphy* provides the framework for the interpretation of geological history, together with relative or chronometric age determinations. Lithostratigraphy refers to sequences of lithological units (see Figure 1). In archaeology, the "rock strata" are instead layers containing cultural remains, which are assumed to represent meaningful entities, often referred to as cultures, cultural traditions, cultural facies, industries, etc. (Clark, 1991). While the geological use of chronostratigraphy is aimed at validating synchronicity and sequences in worldwide systems, the term is only regionally applicable in archaeology because human cultural entities are not worldwide in extent. However, if contemporaneous cultural units from different regions are regarded as facies, it is possible to construct chronostratigraphies on a coarse scale. Even though chronostratigraphies of human cultural history can also be event based, the recognizable results of events are neither as universal nor contemporaneous as they can be in geology, where such events are especially exploited in the construction of chronostratigraphies.

In either case, the scale in time and/or space determines the validity (and construction) of any given chronostratigraphy, because geological and archaeological phenomena operate at different scales (Dean, 1993). The scales are mainly dictated by the nature of the record; they vary with time but are also different between disciplines (Stein, 1993), especially in archaeology, where change over time can be rapid (Blackwell and Schwarcz, 1993). Chronostratigraphies should be based on several independent lines of evidence for time sequences, such as the use of various relative stratigraphies (e.g., lithostratigraphic, magnetic, or biological) combined with chronometric age estimates developed through multiple dating techniques. Lithostratigraphic and biostratigraphic units can have diachronous or time-transgressive boundaries – i.e., variable lower starting points and upper ending points – but chronostratigraphic units always (by definition) have synchronous boundaries – i.e., start and end points are globally coeval (Holliday, 1993).

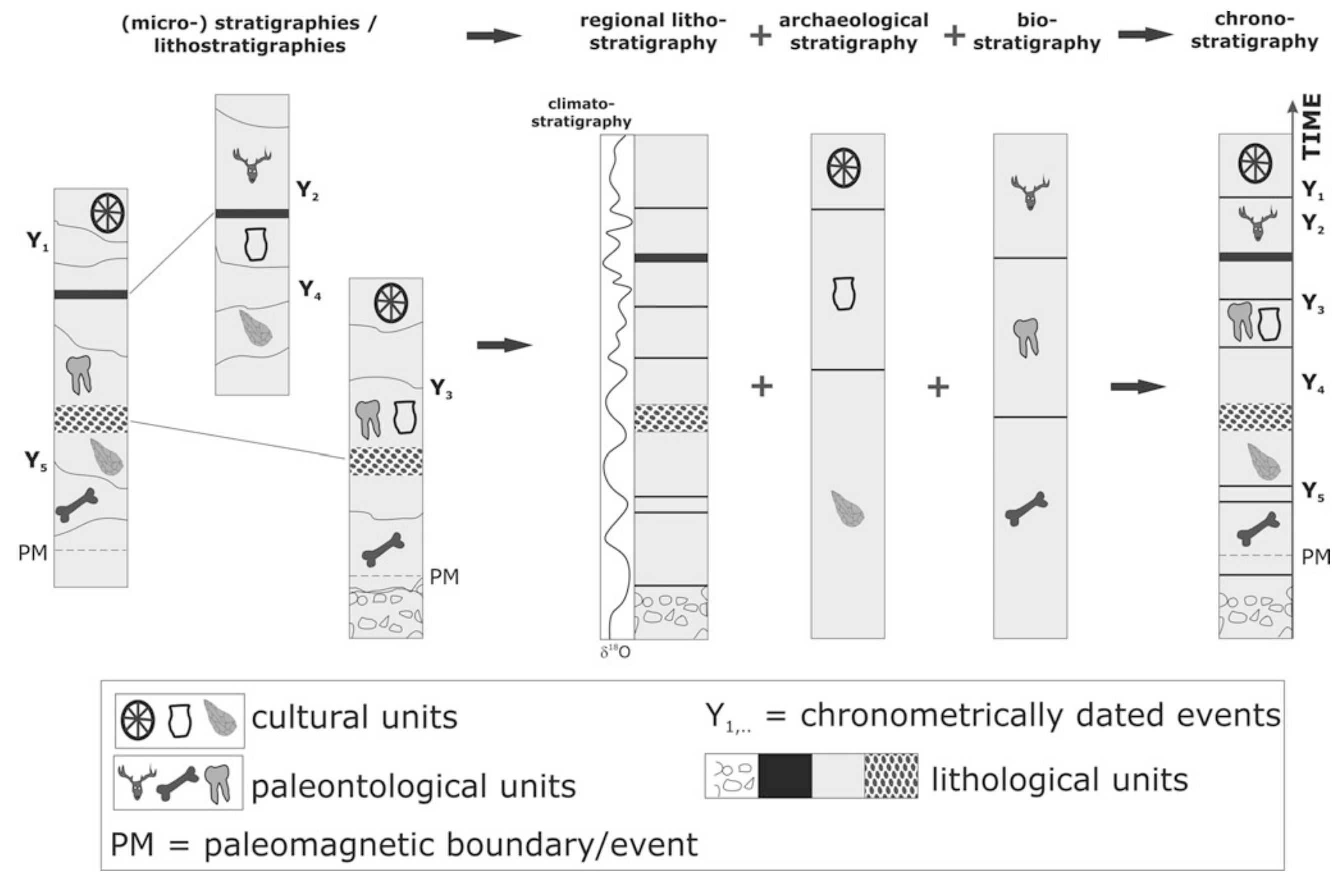
Geological chronostratigraphy

Geological chronostratigraphy is based on lithostratigraphies (Figure 1), and in contrast to archaeology, they are formalized and aimed toward global applicability (Miall, 2010). Global Boundary Stratotype Sections and Points (GSSP) are defined through internationally agreed upon stratigraphic sections or marker horizons, which are governed by international bodies (see http://www.stratigraphy.org and Remane, 1997, 2003). Such boundaries on the geologic time scale are based on paleontological changes (*biostratigraphy* as in the relative sequences of bone –tooth – antler in Figure 1), isotopic marker horizons (as in *climatostratigraphy*), or magnetic events (as in *paleomagnetic dating*), which can be traced over large geographical areas (Rey and Galeotti, 2008). The base of a chronostratigraphic unit is identified in a certain stratigraphic section, while the end of that unit is defined as the base of the following chronostratigraphic unit, which can be defined from evidence in a different section at some distance from the first. Such units are isochronous bodies that are bound by synchronous surfaces and formed during a single span of time (Cremeens and Hart, 1995).

Specific chronostratigraphies, like isotope chronostratigraphy (*climostratigraphy*; Baskaran, 2011; Bowen, 2011), *biostratigraphy* (Palombo and Sardella, 2007), or magneto-chronostratigraphy/*paleomagnetic dating* (Opdyke and Channell, 1996), refer to the construction of a time series using one specific method (i.e., analysis of isotopic chemistry, biota, or magnetism) to provide relative age information.

Archaeological chronostratigraphy

Chronostratigraphy in archaeology follows the same general principles as in geology (Lyman and O'Brien, 2000), but it is less strict and less formalized, given the impossibility of a worldwide application because human culture is so diverse, and there is great potential for large time gaps and sparseness of available data. *Archaeological stratigraphies* are constructed from the time series provided by their own lithostratigraphies, in which specific features related to cultural remains (like stone tools, ceramics, etc.), or the typological/technological compositions of the cultural remains, are repeatedly observed in strata within stratigraphies. Such entities are defined and assumed to represent meaningful units of human cultural history in space and time (cultural traditions, cultural facies, industries, horizon style, etc.), reflecting normative



Chronostratigraphy, Figure 1 Schematic representation of the construction of chronostratigraphies. The cultural units for archaeological stratigraphies are represented by hand axes, pots, and wheels; the lithological units are depicted as having different signatures (bones, teeth, and antlers) representing biostratigraphical units. Chronometric age estimates are marked by "Y" (based on specific dating methods) and paleomagnetic events by "PM." A regional lithostratigraphy is first constructed on the basis of the lithological units combined with climatostratigaphy ($\delta^{18}O$ curve). By combining the archaeological and biological stratigraphies, together with chronometric ages and the paleomagnetic event, a chronostratigraphy is established, which serves archaeology, geology, and paleontology.

ideas and mental templates of extinct people (Clark, 1991). An unspecified number of archaeological assemblages showing more or less identical patterns are necessary to define such a cultural unit, which is understood to demonstrate the shared behavior reflected by a human society and, thus, a socioeconomically meaningful unit (as represented by the hand axe, pot, and wheel in Figure 1). However, any chronostratigraphic marker or event concept in geology is widespread, whereas the definitions of specific features/items of cultural remains are often based on typology (chronotypology after Clark, 1991), which can be quite localized and of limited regional extent.

The resulting cultural units provide the basic relative stratigraphic framework (e.g., the relative sequence of hand axe–pot–wheel in Figure 1), similar to *lithostratigraphy* and *biostratigraphy* (e.g., the relative sequence of bone–tooth–antler in Figure 1), sometimes sharing the type fossil (O'Brien and Lyman, 1999) or the assemblage (Clarke and Chapman, 1978) approach with paleontology. By incorporation of other relative (paleomagnetic event "PM" in Figure 1), as well as chronometric data (Y in Figure 1), chronostratigraphies are constructed on variable scales in time and geography. Linking the archaeological remains of formerly occupied sites to the paleoclimatic record ($\delta^{18}O$ curve in Figure 1) allows more precise age estimates than would be obtainable by many chronometric dating methods, subsequently increasing the precision of the chronostratigraphies.

The resulting regional archaeological chronostratigraphies can overlap and do not necessarily correspond in time, number, or definition of units. Furthermore, archaeological chronostratigraphic units are sometimes blurred by imprecise definitions and by circular logic, e.g., when the supposed age, not the actual cultural remains themselves, is used as an argument for the attribution of an archaeological assemblage to a cultural unit. Archaeological chronostratigraphic units (sometime called phases) can have boundaries coincident with the bases of geological ones, or they can overlap. Obviously, geological and archaeological chronostratigraphic units do not have to correspond, especially as the relationship of cultural remains and geological/sedimentological processes are not always clearly defined. Such specificities like pedostratigraphy and related chronostratigraphies, especially with reference to archaeology, are discussed in detail in Cremeens and Hart (1995).

Bibliography

Baskaran, M., 2011. *Handbook of Environmental Isotope Geochemistry*. Heidelberg: Springer. Advances in Isotope Geochemistry Series.

Blackwell, B. A., and Schwarcz, H. P., 1993. Archaeochronology and scale. In Stein, J. K., and Linse, A. R. (eds.), *Effects of Scale on Archaeological and Geoscientific Perspective*. Boulder: Geological Society of America. Geological Society of America Special Paper 283, pp. 39–58.

Bowen, R., 2011. Isotopic paleoclimatology. In Vértes, A., Nagy, S., Klencsár, Z., Lovas, R. G., and Rösch, F. (eds.), *Handbook of Nuclear Chemistry*, 2nd edn. Dordrecht: Springer, pp. 727–760.

Clark, G. A., 1991. *Perspectives on the Past: Theoretical Biases in Mediterranean Hunter-Gatherer Research*. Philadelphia: University of Pennsylvania Press.

Clarke, D. L., and Chapman, R., 1978. *Analytical Archaeology*, 2nd edn. New York: Columbia University Press.

Cremeens, D. L., and Hart, J. P., 1995. On chronostratigraphy, pedostratigraphy, and archaeological context. In *Pedological Perspectives in Archaeological Research: Proceedings of Two Symposia Sponsored by Division S-5 of the Soil Science Society of America, Cincinnati, 8 November 1993*. SSSA Special Publication 44. Madison, WI: Soil Science Society of America, pp. 15–33.

Dean, J. S., 1993. Geoarchaeological perspectives on the past: chronological considerations. In Stein, J. K., and Linse, A. R. (eds.), *Effects of Scale on Archaeological and Geoscientific Perspectives*. Boulder: Geological Society of America. Geological Society of America Special Paper 283, pp. 59–66.

Holliday, V. T. (ed.), 1993. *Soils in Archaeology: Landscape Evolution and Human Occupation*. Washington: Smithsonian Institution Press.

Lyman, R. L., and O'Brien, M. J., 2000. Chronometers and units in early archaeology and paleontology. *American Antiquity*, **65**(4), 691–707.

Miall, A. D., 2010. *The Geology of Stratigraphic Sequences*, 2nd edn. Heidelberg: Springer.

O'Brien, M. J., and Lyman, R. L., 1999. *Seriation, Stratigraphy, and Index Fossils: The Backbone of Archaeological Dating*. New York: Kluwer/Plenum.

Opdyke, N. D., and Channell, J. E. T., 1996. *Magnetic Stratigraphy*. San Diego: Academic Press. International Geophysics Series, Vol. 64.

Palombo, M. R., and Sardella, R., 2007. Biochronology and biochron boundaries: a real dilemma or a false problem? An example based on the Pleistocene large mammalian faunas from Italy. *Quaternary International*, **160**(1), 30–42.

Remane, J., 1997. Chronostratigraphic standards: how are they defined and when should they be changed? *Quaternary International*, **40**(1), 3–4.

Remane, J., 2003. Chronostratigraphic correlations: their importance for the definition of geochronologic units. *Palaeogeography Palaeoclimatology Palaeoecology*, **196** (1–2), 7–18.

Rey, J., and Galeotti, S., 2008. *Stratigraphy: Terminology and Practice*. Paris: Editions Technip.

Stein, J. K., 1993. Scale in archaeology, geosciences, and geoarchaeology. In Stein, J. K., and Linse, A. R. (eds.), *Effects of Scale on Archaeological and Geoscientific Perspectives*. Boulder: Geological Society of America. Geological Society of America Special Paper 283, pp. 1–10.

Cross-references

Archaeological Stratigraphy
Archaeomagnetic Dating
Climatostratigraphy
Cosmogenic Isotopic Dating
Microstratigraphy
Oxygen Isotopes
Paleomagnetism
Sedimentology
Soil Stratigraphy

CLIMATOSTRATIGRAPHY

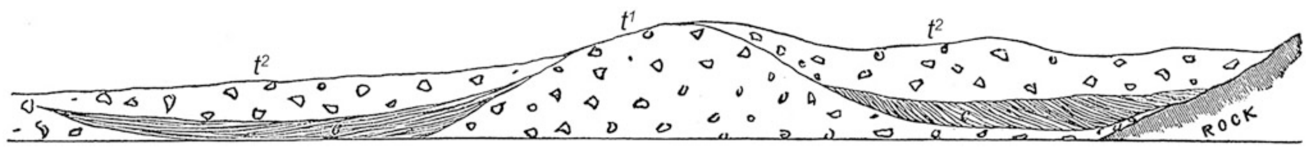
Philip L. Gibbard
Cambridge Quaternary, Department of Geography, University of Cambridge, Cambridge, UK

Definition and introduction

That part of geological time most germane in archaeology, the Quaternary Period, has long been subdivided on the basis of represented climatic changes. The overriding influence of climatic change on geological processes in the Quaternary has meant that climate-based classification (referred to as climatostratigraphy or climostratigraphy) has remained central to the subdivision of the succession. This entry discusses the role of climatostratigraphy (geologic-climate classification) and its relation to chronostratigraphy for the division of the Quaternary sequence.

Climatostratigraphy ("climostratigraphy")

Since the middle of the nineteenth century, Quaternary sediment sequences, and therefore the chronology of human activity and evolution, have traditionally been divided on the basis of the climatic changes they represent, particularly sequences based on glacial deposits in central Europe and mid-latitude North America. This approach was adopted by early workers for terrestrial sequences because it seemed logical to divide glacial diamicton (unconsolidated, poorly sorted sediments) and non-glacial deposits found in stratigraphic sequences into *glacial* (*glaciation*) and *interglacial* periods, respectively (cf. West, 1968, 1977; Bowen, 1978). In other words, the divisions were fundamentally lithological (Figure 1). The overriding influence of climatic change on sedimentation and erosion during the Quaternary has meant that, despite the enormous advances in knowledge during the



Climatostratigraphy, Figure 1 Fossiliferous sand deposits (shown by diagonal cross hatching) between tills (shown by angular symbols) exposed in the Cowden Burn railway cutting at Neilston in Renfrewshire, Scotland, reproduced from Geikie (1874, Figure 27).

last 150 years, climate-based classification has remained central to the subdivision of the succession. Indeed, the subdivision of the modern isotope (e.g., Railsback et al., 2015) stage sequence of ocean sediments is itself based on the same basic concept (e.g., Railsback et al. 2015). It is this approach which has brought Quaternary geology so far, but at the same time, it causes considerable confusion to workers attempting to correlate sequences from enormously differing geographical, and thus environmental, settings. This is because of the great complexity of climatic change and the very variable effects these changes impose upon natural systems, including humans.

The recognition of past climatic events based on environmental indicators within sediments is an inferential method and by no means straightforward. Sediments are not unambiguous indicators of contemporaneous climate, so that other evidence – such as fossil assemblages, characteristic sedimentary structures (including periglacial structures) or textures, soil development, etc. – must be relied upon wherever possible to determine the origin and climatic affinities of a particular unit. Local and regional variability of climate complicates this approach because particular sequences are always the result of local climatic and environmental conditions, yet there remains the need and desire to equate them to a global scale. For at least the first half of the twentieth century, the preferred scale was that developed for the Alps at the turn of the twentieth century by Penck and Brückner (1909) (Table 1).

Since the mid-twentieth century, a comparable scheme developed in northern Europe has been dominant, at least in Europe, but similar schemes have also been established elsewhere, such as in North America or the former USSR. More recently, these schemes have tended to be replaced by the marine- or ice-core oxygen isotope records. Today, the burden of correlation lies in equating local, highly fragmentary, yet high-resolution terrestrial and shallow marine sediment records on the one hand, with the potentially continuous, yet comparatively lower resolution isotope sequence from oceanic sediments on the other (cf. Gibbard and van Kolfschoten, 2005).

Terminology

Before the impact of the ocean-core isotope sequences, an attempt was made to formalize the climate-based stratigraphic terminology in the American Code of

Climatostratigraphy, Table 1 The Alpine sequence in increasing age, as proposed by Penck and Brückner (1909), with later additions from Doppler et al. (2011). Transition dates provided where they are known

Postglacial (Holocene)	← ca. 11.7 ka
Würm glacial (Würmian)	← ca. 117 ka
Riss/Würm interglacial	← ca. 128 ka
Riss glacial (Rissian)	← ca. 350 ka
Mindel/Riss interglacial	
Mindel glacial (Mindelian)	
Günz/Mindel interglacial	
Günz glacial	
Donau/Günz interglacial	
Donau glacial	
?Biber glacial	← ca. 2,600 ka

Stratigraphic Nomenclature (American Commission on Stratigraphic Nomenclature, 1961), where the so-called geologic-climate units were proposed. Here, a geologic-climate unit was based on an inferred widespread climatic episode defined from a subdivision of Quaternary rocks. Several synonyms for this category of unit have been suggested, the most recent being climatostratigraphical units (Mangerud et al., 1974) in which an hierarchy of terms is proposed. In subsequent stratigraphic codes, however (see Hedberg, 1976; North American Commission on Stratigraphic Nomenclature, 1983; Salvador, 1994), the climatostratigraphic approach has been discontinued since it was considered that for most of the geological column, "inferences regarding climate are subjective and too tenuous a basis for the definition of formal geologic units" (North American Commission on Stratigraphic Nomenclature, 1983, 849). This view has not found favor with Quaternary scientists, however, since it is difficult to envisage a scheme of stratigraphic subdivision for recent earth history that does not specifically acknowledge the climate change factor (Lowe and Walker, 1997). Accordingly, Quaternary stratigraphic sequences continue to be divided into geologic-climatic units based on proxy climatic indicators, and hence, following this approach, the Pleistocene-Holocene boundary (the base of the Holocene series/epoch), for example, is defined on the basis of the inferred climatic record (cf. below). Boundaries between geologic-climate units were placed at the transitions between those the stratigraphic units on which they were based.

The American Code (1961) defines the fundamental units of the geologic-climate classification as follows:

A *glaciation* is a climatic episode during which extensive glaciers developed, attained a maximum extent, and receded. A *stadial* ("stade") is a climatic episode, representing a subdivision of a glaciation, during which a secondary advance of glaciers took place. An *interstadial* ("interstade") is a climatic episode within a glaciation during which a secondary recession or standstill of glaciers took place.

An *interglacial* ("interglaciation") is an episode during which the climate was incompatible with the wide extent of glaciers that characterize a glaciation.

In Europe, following the work of Jessen and Milthers (1928), it is customary to use the terms interglacial and interstadial to define characteristic types of non-glacial climatic conditions indicated by vegetational changes. Interglacial describes a temperate period with a climatic optimum at least as warm as the present interglacial (Holocene, Flandrian: see below) in the same region, and interstadial describes a period that was either too short or too cold to allow the development of temperate deciduous forest or the equivalent of interglacial type in the same region (West, 1977, 1984).

In North America, mainly in the USA, the term *interglaciation* is occasionally used for interglacial (cf. American Code, 1961). Likewise, the terms *stade* and *interstade* may be used instead of stadial and interstadial, respectively (cf. American Code, 1961). The origin of these terms is not certain, but the latter almost certainly derive from the French language word *stade* (m), which is unfortunate since in French, *stade* means (chronostratigraphical) stage (cf. Michel et al., 1997), e.g., *stade isotopique marin* = marine isotope stage.

It will be readily apparent that, although in longstanding usage, the glacially based terms are very difficult to apply outside glaciated regions. Moreover, as Suggate and West (1969) recognized, the term glaciation or glacial is particularly inappropriate since modern knowledge indicates that cold rather than glacial climates have tended to characterize the periods intervening between interglacial events over most of the earth. They therefore proposed that the term "cold" stage (chronostratigraphy) be adopted for "glacial" or "glaciation." Likewise, they proposed the use of the term "warm" or "temperate" stage for interglacial, both being based on regional stratotypes. Lüttig (1965) also recognized this problem and attempted to avoid the glacial connotations by proposing the terms *cryomer* and *thermomer* for cold and warm periods, respectively. These terms have found little acceptance, however. The local nature of these definitions indicates that they cannot necessarily be used inclusively over great distances or between different climatic provinces (Suggate and West, 1969; Suggate, 1974; West, 1977, 1984) or indeed across the terrestrial/marine facies boundary (see below). In addition, it is worth noting that the subdivision into glacial and interglacial is mainly applied to the Middle and Late Pleistocene (i.e., the last 0.78 Ma).

Boundaries

Perhaps the biggest problem with climate-based nomenclature is where the boundaries should be drawn. Ideally, they should be placed at the climate change, but since the events are recognized only through the responses they initiate in depositional or biological systems, a compromise must be agreed upon. As Bowen (1978) emphasizes, there are many places at which boundaries could be drawn, but in principle, they are generally placed at midpoints between temperature maxima and minima, e.g., in ocean-sediment sequences. This positioning is arbitrary but is necessary because of the complexity of climatic changes. Problems may arise, however, when attempts are made to determine the chronological relationship of boundaries drawn in sequences that possess differing temporal resolution, show different sediment facies, or originate through the use of differing proxies. By contrast, in temperate northwest Europe, the base of an interglacial or interstadial is very precisely defined. It is placed at the point where herb-dominated (cold climate) vegetation is replaced by forest. The top (i.e., the base of the subsequent glaciation or cold stage) is drawn where the reversal occurs (Jessen and Milthers, 1928; Turner and West, 1968). It is unclear, however, how this relates to the timing of the actual climate change recorded, or how this is recorded by other proxies.

Climatostratigraphic units are not chronostratigraphic units

By the second half of the twentieth century, it was realized that Quaternary time should be subdivided as far as possible in keeping with the rest of the geological column – using time, or chronostratigraphy, as the basic criterion (e.g., van der Vlerk, 1959; Gibbard and West, 2000). Because stages are the fundamental working units in chronostratigraphy, they are considered appropriate in scope and rank for practical intraregional classification (Hedberg, 1976). However, the definition of chronostratigraphical units at the status of stage, with their time-parallel boundaries placed in continuous successions wherever possible, is a serious challenge especially in terrestrial Quaternary climate-dominated sequences. In these situations, boundaries in a region may be time parallel, but over greater distances, problems may arise as a result of diachroneity. It is probably correct to say that only in continuous sequences which span entire interglacial-glacial-interglacial climatic cycles can an unequivocal basis for the establishment of stage events using climatic criteria be truly successfully achieved. There are the additional problems which accompany such a definition of a stage, including the question of diachroneity of climate changes themselves and the detectable responses to those changes.

For example, it is well known that there are various "lag" times of geological, biological, and human responses to climatic stimuli. Thus, in short, climate-based units cannot be the direct equivalents of chronostratigraphical units because of the time-transgressive nature of the former. This distinction of a stage in a terrestrial sequence from that in a marine sequence should be remembered when correlation is attempted.

In general practice today, these climatic subdivisions have been used interchangeably with chronostratigraphical stages by the majority of workers. While this approach, which gives rise to alternating "cold" and "warm" or "temperate" stages, has been advocated for 50 years, there remains considerable confusion about the precise distinction between the schemes, particularly among non-geologists. In Europe, many of the terms in current use, perhaps surprisingly, do not have defined boundary or unit stratotypes. This problem has been recognized, and steps are now being taken to define units formally through the work of the INQUA Subcommission on European Quaternary Stratigraphy (SEQS). Many fail to see the need for this, however, especially those who rely on geochronology, particularly radiocarbon, for correlation. For example, despite repeated attempts to propose a GSSP boundary stratotype for the base of the Holocene Series – i.e., the Pleistocene-Holocene (Weichselian-"Flandrian") boundary (Olausson, 1982) – in the past, only recently has a universally acceptable boundary been defined (Walker et al., 2008).

Nomenclatural complexities

As already stated, the situation is more confused in languages other than English. For example, in German the terms *glazial* and *interglazial* are used as equivalents to the English stage. Such an approach, on the face of it, seems expedient until one considers certain stages that have been correctly, formally defined in the Middle and Early Pleistocene of the Netherlands, which are commonly used throughout Europe. Here the Bavelian Stage includes two interglacials and two glacials; likewise the Tiglian Stage comprises at least three interglacials and two glacials (de Jong, 1988; Zagwijn, 1992). Each of these interglacials is comparable in their characteristics to the last interglacial or Eemian, which is a discrete stage, which is also defined in the Netherlands. In these cases, workers have fallen back on the noncommittal term *complex*. One example is the Saalian of Germany, originally defined as a glaciation. This chronostratigraphical stage includes at least one interglacial and potentially a second, as currently defined (Litt and Turner, 1993). Attempts to circumvent the nomenclatural problem by defining a "Saalian Complex" are a fudge at best but one that is occasioned by linguistic and long-term historical precedent, as much as by geological needs.

Global correlation

The original intention was that "cold" or "warm" or "temperate" stages should represent the first-rank climate oscillations recognized in the geological record, although it has since been realized that some, if not all, are internally complex. Subdivision of these stages into substages or zones was to be based, in the case of temperate stages, on biostratigraphy, and in the case of cold stages principally on lithostratigraphy and or pedostratigraphy. Within the range of radiocarbon dating (ca. 30 ka), the most satisfactory form of subdivision is frequently that based on radiocarbon years (cf. Shotton and West, 1969); however, high-resolution investigations, such as the ice-core investigations, have allowed the recognition of ever more climatic oscillations of decreasing intensity or wavelength within the first-rank time divisions. These events are stretching the ability of the stratigraphical terminology to cope with the escalating numbers of names they generate. Terms such as "event," "oscillation," or "phase" are currently in use to refer to short or small-scale climatic events (often referred to as "sub-Milankovitch oscillations"). Clear hierarchical patterns are becoming blurred, but perhaps this should be seen as a positive development since the system must reflect the need to classify events that are recognized. Moreover, as our ability to resolve increasingly smaller-scale oscillations improves, a more detailed nomenclature will inevitably emerge. One possible approach is to avoid attempted chronostratigraphical classification in favor of an event scheme based on the recognition of "diachronic units" (e.g., Curry et al., 2011) or event stratigraphy, but in practice this differs little from that based on climate.

Therefore, for many geologists and archaeologists, chrono- and climatostratigraphical terminology are interchangeable. Although realistically, this situation is clearly unsatisfactory because of the imprecision that it may bring to interregional and ultimately to global correlation, it is likely to continue for the foreseeable future. The long-term goal should be to clarify the situation by continuing to develop a formally defined, chronostratigraphically based system that is fully compatible with the rest of the geological column, supported by reliable geochronology.

Bibliography

American Commission on Stratigraphic Nomenclature, 1961. Code of stratigraphic nomenclature. *Bulletin of the American Association of Petroleum Geologists*, **45**(5), 645–665.

Bowen, D. Q., 1978. *Quaternary Geology: A Stratigraphic Framework for Multidisciplinary Work*. Oxford: Pergamon Press.

Curry, B. B., Grimley, D. A., and McKay, E. D., III, 2011. Quaternary glaciations in Illinois. In Ehlers, J., Gibbard, P. L., and Hughes, P. D. (eds.), *Quaternary Glaciations—Extent and Chronology – A Closer Look*, 2nd edn. Amsterdam: Elsevier. Developments in Quaternary Science, Vol. 15, pp. 467–487.

De Jong, J., 1988. Climatic variability during the past three million years, as indicated by vegetational evolution in northwest Europe and with emphasis on data from The Netherlands. *Philosophical Transactions of the Royal Society of London B*, **318**(1191), 603–617.

Doppler, G., Kroemer, E., Rögner, K., Wallner, J., Jerz, H., and Grottenthaler, W., 2011. Quaternary stratigraphy of southern Bavaria. *Eiszeitalter und Gegenwart*, **60**(2–3), 329–365.

Geikie, J., 1874. *The Great Ice Age, and Its Relation to the Antiquity of Man*. London: W. Isbister.
Gibbard, P. L., and van Kolfschoten, T., 2005. Pleistocene and Holocene epochs. In Gradstein, F. M., Ogg, J. G., and Smith, A. G. (eds.), *A Geologic Time Scale 2004*. Cambridge: Cambridge University Press, pp. 441–452.
Gibbard, P. L., and West, R. G., 2000. Quaternary chronostratigraphy: the nomenclature of terrestrial sequences. *Boreas*, **29**(4), 329–336.
Hedberg, H. D., 1976. *International Stratigraphic Guide: A Guide to Stratigraphic Classification, Terminology, and Procedure*. New York: Wiley.
Jessen, K., and Milthers, V., 1928. *Stratigraphical and Paleontological Studies of Interglacial Fresh-Water Deposits in Jutland and Northwest Germany*. Danmarks Geologisk Undersøgelse, II Raekke, No. 48. København: Reitzel.
Litt, T., and Turner, C., 1993. Arbeitserbgenisse der Subkommission für Europäische Quartärstratigraphie: Die Saalesequenz in der Typusregion (Berichte der SEQS 10). *Eiszeitalter und Gegenwart*, **43**(2), 125–128.
Lowe, J. J., and Walker, M. J. C., 1997. *Reconstructing Quaternary Environments*, 2nd edn. London: Longmans.
Lüttig, G., 1965. Interglacial and interstadial periods. *Journal of Geology*, **73**(4), 579–591.
Mangerud, J., Andersen, S. T., Berglund, B. E., and Donner, J. J., 1974. Quaternary stratigraphy of Norden, a proposal for terminology and classification. *Boreas*, **3**(3), 109–126.
Michel, J.-P., Fairbridge, R. W., and Carpenter, M. S. N., 1997. *Dictionnaire des Sciences de la Terre*, 3rd edn. Paris/Chichester: Masson/Wiley.
North American Commission on Stratigraphic Nomenclature, 1983. North American stratigraphic code. *American Association of Petroleum Geologists Bulletin*, **67**(5), 841–875.
Olausson, E. (ed.), 1982. *The Pleistocene/Holocene Boundary in South-Western Sweden*. Avhandlingar och Uppsatser/Sveriges Geologiska Undersökning, Serie C, nr. 794. Uppsala: Sveriges Geologiska Undersökning.
Penck, A., and Brückner, E., 1909. *Die Alpen im Eiszeitalter. 1 Die Eiszeiten in den nördlichen Ostalpen*. Leipzig: Tauchnitz.
Railsback, L. B., Gibbard, P. L., Head, M. J., Voarintsoa, N. R. G., and Toucanne, S., 2015. An optimized scheme of lettered marine isotope substages for the last 1.0 million years, and the climatostratigraphic nature of isotope stages and substages. *Quaternary Science Reviews*, **111**, 94–106.
Salvador, A., 1994. *International Stratigraphic Guide: A Guide to Stratigraphic Classification, Terminology, and Procedure*, 2nd edn. Trondheim/Boulder, CO: International Union of Geological Sciences/Geological Society of America.
Shotton, F. W., and West, R. G., 1969. Stratigraphical table of the British Quaternary. Appendix B1. In George, T. N., Harland, W. B., Ager, D. V., Ball, H. W., Blow, H. W., Casey, R., Holland, C. H., Hughes, N. F., Kellaway, G. A., Kent, P. E., Ramsbottom, W. H. C., Stubblefield, J., and Woodland, A. W. (eds.), *Recommendations on Stratigraphical Usage. Proceedings of the Geological Society of London*, **165**, 155–157.
Suggate, R. P., 1974. When did the last interglacial end? *Quaternary Research*, **4**(3), 246–252.
Suggate, R. P., and West, R. G., 1969. Stratigraphic nomenclature and subdivision in the Quaternary. Working Group for Stratigraphic Nomenclature, INQUA Commission for Stratigraphy (unpublished discussion document).
Turner, C., and West, R. G., 1968. The subdivision and zonation of interglacial periods. *Eiszeitalter und Gegenwart*, **19**(1), 93–101.
Van der Vlerk, I. M., 1959. Problems and principles of tertiary and quaternary stratigraphy. *Quarterly Journal of the Geological Society of London*, **115**(1–4), 49–64.
Walker, M., Johnsen, S., Rasmussen, S. O., Steffensen, J.-P., Popp, T., Gibbard, P., Hoek, W., Lowe, J., Andrews, J., Björck, S., Cwynar, L. C., Hughen, K., Kershaw, P., Kromer, B., Litt, T., Lowe, D. J., Nakagawa, T., Newnham, R., and Schwander, J., 2008. The Global Stratotype Section and Point (GSSP) for the base of the Holocene Series/Epoch (Quaternary System/Period) in the NGRIP ice core. *Episodes, Journal of International Geosciences*, **31**(2), 264–267.
West, R. G., 1968. *Pleistocene Geology and Biology: With Especial Reference to the British Isles*, 1st edn. London: Longmans.
West, R. G., 1977. *Pleistocene Geology and Biology: With Especial Reference to the British Isles*, 2nd edn. London: Longmans.
West, R. G., 1984. Interglacial, interstadial and oxygen isotope stages. *Dissertationes Botanicae*, **72**, 345–357.
Zagwijn, W. H., 1992. The beginning of the ice age in Europe and its major subdivisions. *Quaternary Science Reviews*, **11**(5), 583–591.

COASTAL SETTINGS

Patrick D. Nunn
Australian Centre for Pacific Islands Research,
The University of the Sunshine Coast, Maroochydore, QLD, Australia

Synonyms

Coastal contexts; Coastal habitats

Definition

Within at least the last 70,000 years of human history, coasts have been favored increasingly as places for people to settle, typically in order to take advantage of coastal foods, as well as places from which to interact readily with other human groups (Bailey and Parkington, 1988). Long-standing claims that coasts stimulated the development of agriculture by allowing *Homo sapiens* a unique opportunity to domesticate plants (Sauer, 1962; Binford, 1968) remain credible. Yet it is also apparent that "many of the world's coastlines that have the most productive environmental conditions for heavy dependence on marine and intertidal resources . . . were only colonised by human populations relatively recently" (Bailey, 2004, 41). Coastal food exploitation was so important to some societies that it came to define them (Szabó and Amesbury, 2011; Jew et al., 2013), whereas for others it was less important, something that might feature in societal subsistence only during periods when preferred options were unavailable (Holdaway et al., 2002; Cleuziou and Tosi, 2007).

Food was only one reason why humans have been attracted to coasts throughout the past 100,000 years. The relative ease of movement along coastal strips, where intervening barriers like mountain ranges are less common than in inland areas, meant that the main movements of many early human groups were along continental coasts (Davidson, 2013). Later, as maritime networks became important for trade, coasts were increasingly settled, a major factor in explaining the subsequent concentration of people in coastal cities (von Glasow et al., 2013).

Owing to their location at the nexus of the lithosphere, hydrosphere, and atmosphere, coasts are among the most changeable of Earth's landscapes and have long posed unique challenges to people who sought to locate their permanent settlements there. Foremost among these challenges are changes to coastal landforms and (food-producing) ecosystems resulting from changes, typically gradual, in the level of the land-sea interface caused by relative sea-level change. More localized changes may result from abrupt tectonic change, the impacts of large waves, and by changes in coastal topography as might be driven by the development of offshore reefs or by changes in process regime such as nearshore sedimentation.

It is important on one hand to understand that coastal settings occupied by humans were and still are invariably dynamic, yet it is also important to appreciate that the present is not necessarily a helpful guide to the past. The processes that control the form of a modern coastline are not always those that existed in the past. Further, many ancient coastal occupation sites are now often far from the modern shoreline, perhaps inland or underwater, emphasizing the susceptibility of coasts to change.

This entry looks first at the most common coastal settings occupied by humans, describing examples from different parts of the world, before discussing the coevolution of coastal environments and coastal societies, illustrating the complexities of this with various examples. Finally there is discussion of several key issues in the contemporary understanding of coastal settings for past human activities.

Common coastal settings

Coastal peoples of the past occupied the full range of coastal settings, but in most parts of the world, they favored a few that – at least at the time of their initial occupation – maximized livelihood opportunities, particularly for subsistence. This means that there are few cliff-top or hinterland locations that were intentionally selected in preference to adjacent coastal lowlands. Exceptions are found on high cliffed oceanic islands such as Rurutu (French Polynesia) and many of those in the Marianas Archipelago (northwest Pacific), either because of the difficulties of occupying the shoreline or because of the impoverished resources it contained compared to elsewhere (Weisler et al., 2010; Amesbury, 2013). Three of the most common coastal settings that became sites for permanent human settlement in almost every part of the world are coastal plains, river mouths, and islands, each of which is discussed separately below.

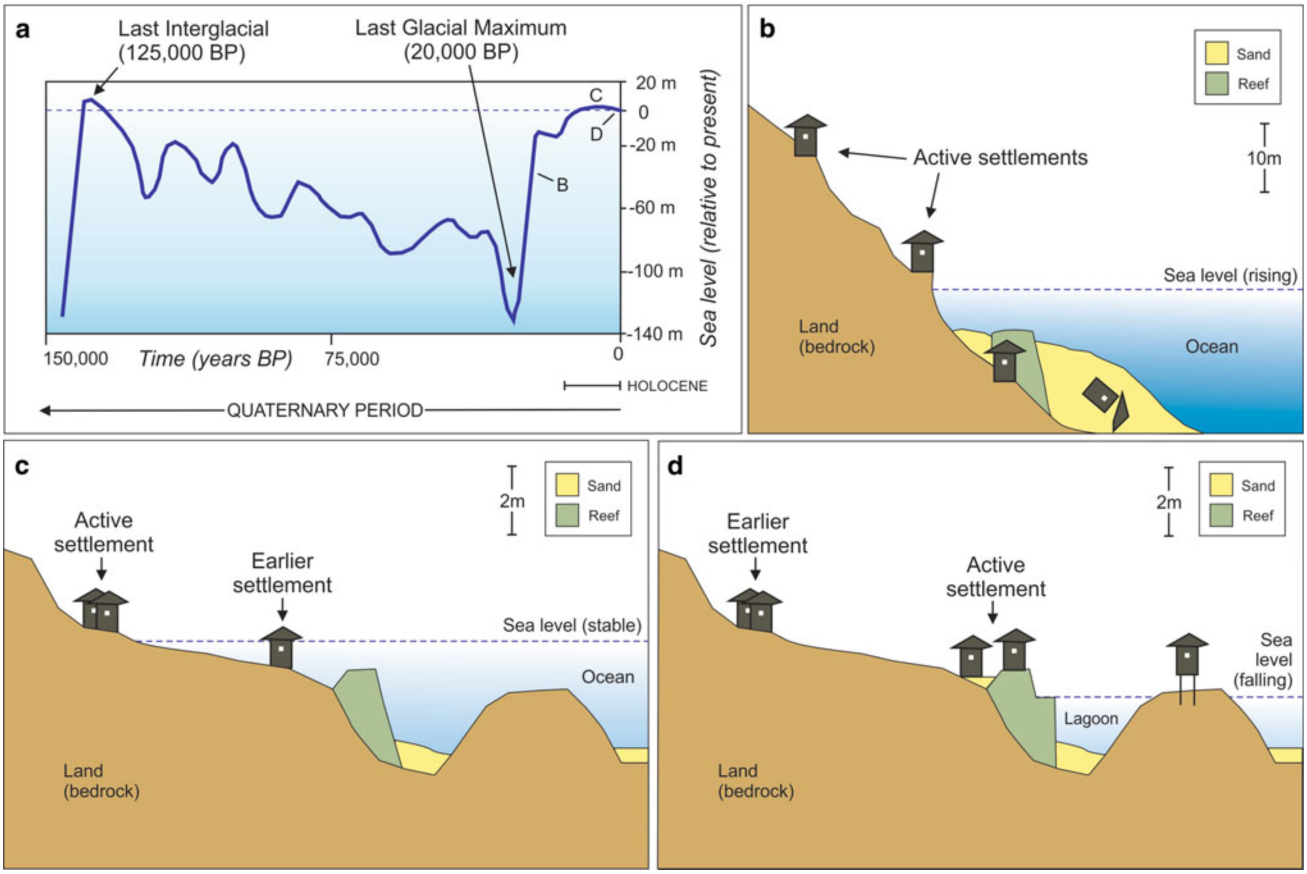
Coastal plains

Varying in breadth from perhaps a few tens of meters, as often found around the fringes of high oceanic islands, to several hundred kilometers, such as were available for human use along many continental margins during the low sea levels of the last glacial period, coastal plains have long attracted humans much as they do today. It can be demonstrated that, at times when population densities were comparatively low, human interest in such coastal plains was proportional to the width of the plain (Lowery et al., 2012).

Human uses of coastal plains more than 4–5 ka ago are invariably difficult to reconstruct because the original environments have disappeared as a result of coastal changes linked to regular (glacial-eustatic) sea-level fluctuations that have characterized the past 2–3 Ma (Figure 1). For this reason, it is challenging to understand, for example, the nature of Pleistocene human occupation on the Australian (Sahul) coastal shelf (O'Connell and Allen, 2012) and that of Doggerland, which linked Britain to continental Europe more than 10,000 years ago (Gaffney et al., 2009).

In many places today, coastal plains represent features created only after sea level fell from its mid-Holocene maximum at 4–6 ka BP (typically 1–2 m above present; see Figure 1d); for this reason, they are found today along most parts of the world's coastline after having become available for human settlement only in the later Holocene (i.e., after 4000 years BP). For example, it has been argued that the initial colonization of the tropical Pacific Islands was controlled by regionally variable sea-level fall in the late Holocene (Dickinson, 2003). More commonly, coastal plains, or at least their younger parts, were occupied progressively as sea level fell during the late Holocene. Haifa Bay and the Zevulun Valley Plain in the eastern Mediterranean exemplify this situation (Porat et al., 2008). As these coastal plains grew seaward with gradual sea-level decline, they were sometimes extended by the accumulation along the coast of sediments derived both from land and shallow offshore (underwater) shelves, particularly those on which (coral-) reef-fringed lagoons had developed. The interplay of erosion and sedimentation accounts for many of the variations in coastal landscapes found along coastal plains. Human manipulation of coastal landscapes sometimes produced unanticipated effects. Examples include the harbors constructed by trading peoples along the coasts of the Mediterranean and Red Sea that subsequently started to infill and, despite ingenious attempts to prevent this, invariably fell into disuse with often profound societal consequences (Marriner and Morhange, 2007; Hein et al., 2011).

Landscape elements of coastal plains are numerous, but those that appear key for most settlers in such settings include sheltered sites, on straight coasts typically behind dunes/berms, beach ridges, or around the fringes of coastal lagoons and wetlands. Examples of back-dune occupations may be found in Fiji and Oman, where they were established by many seasonally transient groups (Anderson et al., 2006; Cavulli and Scaruffi, 2013), and coastal-lagoon occupations were a critical step in the emergence of modern societies along the northeastern New Guinea coast (Terrell, 2002). Occupation sites in



Coastal Settings, Figure 1 Coastal settings influenced by late Quaternary sea-level change. Note that tectonic stability is assumed. (**a**) Global sea-level changes within the last 150,000 years (After Nunn, 1999). (**b**) Coastal environments during the early Holocene at a time of rapid sea-level rise (see (**a**) for timing). Many coasts at this time would have been steep with fewer possibilities for settlement than today. Note the drowned settlements, both buried by sediment and overgrown by reef and those that have been fragmented and dispersed. (**c**) Coastal environments during the middle Holocene at a time when sea level had stabilized at a level 1–2 m higher than today (see (**a**) for timing) resulting in the development of coastal plains and other types of attractive settings for humans. Note how settlements have moved landward as sea level rose toward its maximum and how reefs – along most tropical coasts – have not yet reached the ocean surface. (**d**) Coastal environments during the late Holocene when sea level had fallen to near its present level (see (**a**) for timing) extending low coastal settings seaward and even creating new lands for settlement offshore. Along tropical coasts, some reefs emerged and were used for settlement, while other reefs grew laterally, creating unique ecosystems.

coastal wetlands were generally situated at higher locations where crops might be cultivated to supplement foods obtained from surrounding areas. Lakes were important components of many wetlands. One example is Šventoji (western Lithuania), where the role of late Holocene sea-level oscillations is clear in transforming coastal environments and influencing human lifeways, particularly through the successive creation and infilling of coastal lagoons (Stančikaitė et al., 2009).

Along embayed coasts, it was possible for humans to live directly on the shore in places sheltered from dominant winds and waves. The founder settlement in the Tonga archipelago (southwest Pacific) at Nukuleka was located in the lee of a sand spit at the entrance to the Fanga 'Uta lagoon on the leeward side of Tongatapu Island (Burley and Dickinson, 2001). Spatial and temporal variations in human occupations along the coasts of the sinuous Limfjord (Denmark) were regulated by various physical factors, including salinity and sedimentation (Lewis et al., 2013).

Where a particular coast is fringed by an offshore reef, which reduces the size of waves reaching the shore, shelter was a less important concern, and early settlers sometimes even built stilt-house settlements over shallow water. For example, the use of such settlements is a defining feature of early Lapita colonizers in the southwest Pacific (Green, 2003).

River mouths

River mouths are attractive to humans because of the access both to inland areas and freshwater resources, as well as many coastal resources. Well-documented examples of river-mouth cultures include those around the estuaries of the Irrawaddy (Myanmar), Sông Hồng or Red River (Vietnam), as well as many smaller ones (Stark, 2006). River mouths are often more dynamic environments than coastal plains or most parts of islands, requiring more frequent adjustments by their occupants. A study of archaeological sites at the mouth of the Santa River (Peru) was one of the first to show the dynamic nature of settlement patterns in such places (Wells, 1992: see Figure 4).

Highly valued for their fertile, well-watered soils as well as ready access to aquatic food resources, river deltas are highly dynamic river-mouth environments, and their coastal fringes especially so. Some of the most profound changes have involved abrupt shifts in river mouths that forced changes in the locations of human activities in the past, leading in some cases to migrations and cultural shifts. Examples come from the Huanghe (Yellow) and Yangtze River deltas in coastal China (Chen et al., 2008) and from the Danube Delta in southeastern Europe (Romanescu, 2013). Deltas are especially prone to flooding, yet there are several studies showing how people in the past continued to utilize these areas during wetter periods. An example comes from the Sông Hồng, or Red River, Delta (Vietnam) (Funabiki et al., 2012).

In the past few centuries or more, the dynamics of environmental changes in deltas elsewhere have been so marked that delta cities, well known in antiquity, have proved controversial to rediscover. A good example is Vineta, which was considered to be "the greatest of all cities in Europe" by the traveler Ibrahim Ibn Yaqub in AD 970; it was probably located on a marshy island in the Oder River Delta (Poland) (Brysac, 2003). The city of Herakleion in the Nile Delta (Egypt) likewise disappeared into the realm of myth for several centuries after its abandonment in the first century AD following river-channel shifts and subsidence (Stanley et al., 2004).

Outgrowth of river deltas – a result of both sea-level fall and (accelerated) terrestrial sediment delivery to river mouths – has led to the creation of new areas for coastal settlement that grew in importance in many places. The progradation of the Grijalva Delta (Mexico) witnessed the embryonic emergence of maize cultivation in Mesoamerica, as the first farmers in the region occupied its fertile fringes (Pope et al., 2001).

Islands

Smaller islands may be effectively coastal in their entirety (or very nearly so), and they often exhibit the full range of coastal settings found along the fringes of larger landmasses. Yet on such islands, owing to a lack of large rivers, coasts may feature less dynamic, more resource-rich ecosystems of the kind that perhaps drove, or at least sustained, the successive eastward colonization of tropical Pacific islands (Kennett et al., 2006). At population densities below carrying capacity, islands provided attractive environments for potential settlers because of this resource richness, but also perhaps because their restricted areas made them easier to manage than more diverse landmasses. For example, critical to traditional food production in prehistoric Hawaii was the *ahupua'a* system that involved the vertical integrated management of food systems from the highland island centers downslope, across the coast, and into the deep ocean (Kagawa and Vitousek, 2012).

Yet precisely because of their circumscribed nature, such islands were also susceptible to abandonment by prehistoric populations when resources were no longer sufficient to sustain them. Illustrations of this include the Line Islands (central Pacific) and the Pitcairn Island group (southeast Pacific), both of which were abandoned several hundred years ago (Weisler, 1996; Di Piazza and Pearthree, 2001).

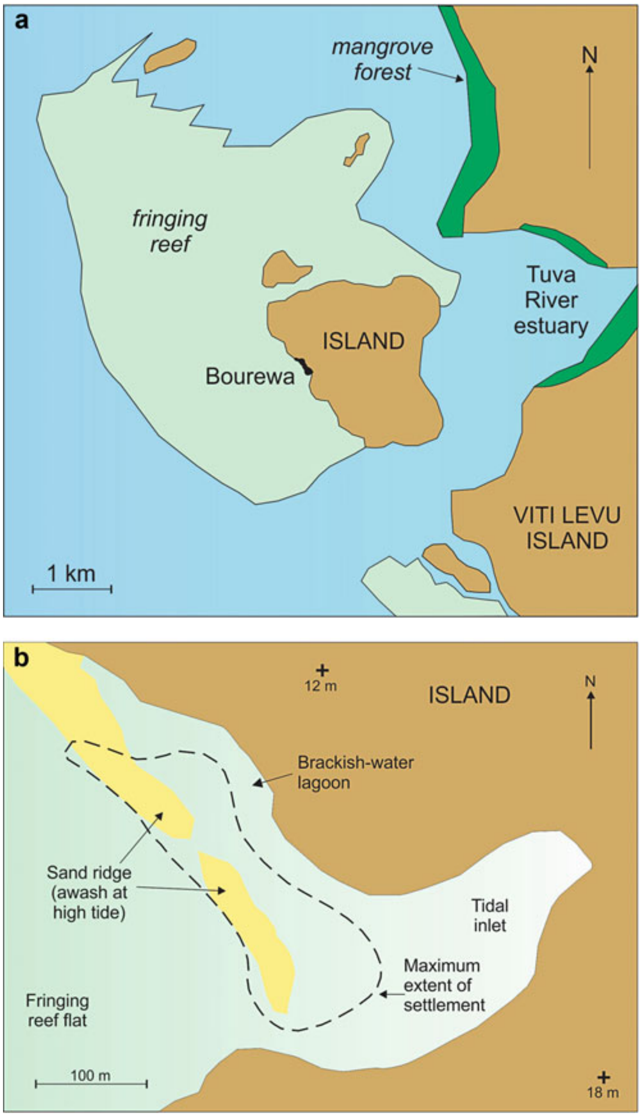
Coastal settings on islands vary largely according to the composition and form of the island in question. Older volcanic islands tend to have irregular coasts with numerous indentations marking drowned river valleys, while younger volcanic islands may have more regular coasts. There is no tradition of coastal settlement along the "iron-bound" (fringed by young, hard lava rock) coasts of young Savai'i Island (Samoa), for example. Most limestone islands are similar, and many of those that have emerged recently possess comparatively little coastal lowland. One example is Niue Island (central Pacific), where most settlement is along a 23-m-high cliff-top terrace (Nunn and Britton, 2004).

There is evidence that the earliest occupants of islands in the southwest Pacific targeted smaller islands intentionally (Specht, 2007), perhaps because these islands tended to be surrounded by more pristine reefs (Figure 2a). Within such islands, the earliest sites were often built on stilt houses across shallow-water flats, which became dry land as sea level fell and as the middens below the houses gradually built upward (Kirch, 2001). One such occupation in Fiji occurred on a sand spit separating a brackish coastal lagoon from a fringing reef flat (Figure 2b).

Atolls are types of low (wholly coastal) island that, in parts of the northwest Pacific, have been occupied continuously for around 2000 years. Their restricted terrestrial biota meant that subsistence was dominated by food acquisition within shallow-water reefs and lagoons, although this came to be supplemented by novel techniques of onshore production (Kayanne et al., 2011).

Changing coastal settings and their effects on coastal societies

As coastal environments were transformed by climate-driven (especially sea-level) and tectonic changes, their



Coastal Settings, Figure 2 Occupation of island fringes illustrated by the (Lapita-age) Bourewa settlement, perhaps the earliest in the Fiji archipelago (southwest Pacific) (After Nunn, 2009a). (**a**) The Lapita peoples were the first to colonize most island coasts in the southwest Pacific. Their earliest settlements were commonly on smaller islands lying off the coast of larger ones, as is the case with Bourewa that was located on an island which is now, owing to sea-level fall, part of the larger Viti Levu Island. It is thought that smaller islands were favored by Lapita people because of their often broad reef flats from which ample foods could be readily obtained. (**b**) The original settlement at Bourewa was a series of stilt-house complexes built over water along the axis of a sand ridge. As sea level fell, this sand ridge emerged to create a partial barrier between the fringing reef on the southwest and a brackish lagoon on the northwest, both environments of which were exploited by the Lapita settlers here.

human occupants were often forced to adapt. Yet humans sometimes altered the coastal landscapes they inhabited, and these modifications often brought about unanticipated responses that also required adaptation.

In earlier societies, adaptation commonly required refocusing subsistence strategies, particularly as food-producing ecosystems changed. In more recent times, owing to the greater potential impacts of humans, it is often more difficult to separate the anthropogenic effects from environmental changes driven by natural causes (see below). The present section illustrates these points by looking at the parallel evolution of coastal environments and societies during specific periods of prehistory. Since the potential for tectonic disruption of coastal sites is not time dependent in the way that climate-driven changes have invariably been, coastal sites affected by tectonism are considered in a separate section.

Pleistocene times (>10,000 years ago)

Some of the first forays out of Africa by *Homo sapiens* may have intentionally followed coastal routes because of the availability of coastal resources (Bailey, 2009). A particular case in point is the southern dispersal route that early humans are thought to have taken from Africa to Southeast Asia (Field et al., 2007), which may have initially involved crossing the Red Sea at a time when sea level was lower and the Bab al-Mandab Straits were relatively easy to cross (Bailey et al., 2007). At such times, presently arid coasts like those of the Farasan Islands and mainland Arabia may have received more rainfall than today, permitting contemporary occupation of a number of coastal settings. There are indications that early humans in this area also targeted nearshore marine resources; some giant clam species show signs of having been overharvested here as much as 125,000 years ago (Richter et al., 2008).

Implicit in the crossing of the Wallace Line from Sunda to Sahul (Southeast Asia to Australia) perhaps 60,000 years ago is a familiarity with tropical coasts that included a degree of maritime technology sufficient to permit the successful crossing of ocean gaps as much as 70 km wide. Most likely, the sites occupied by such humans were on coastal plains fringed by broad reefs or around river mouths where coastal inhabitants depended largely on intertidal and reef-flat food resources but also pelagic resources (Balme, 2013). It is possible that coastal environmental changes, perhaps driven by last glacial sea-level fluctuations, stimulated pioneer occupations of offshore islands in Sunda, leading eventually to the first colonization of Australia and New Guinea (Sahul).

A final example of Pleistocene human interaction with coasts is that involving initial human arrival in the Americas ca. 16,000 BP from the western Pacific Rim, perhaps along a shoreline that is now largely invisible due to submergence by later sea-level rise and fragmentation by differential tectonics (Erlandson and Braje, 2011). These authors note that, at the time, this former shoreline would have been associated with "rich and diverse resources from both marine and terrestrial ecosystems" (p. 28), perhaps a "kelp highway" that could have sustained migrants from Japan through the Kuril Islands to Kamchatka, the southern shores of Beringia, and thence along the ice-free coastal fringe of glacier-covered North America to the California coast from where migrants began to settle onshore and inland (Erlandson et al., 2007).

Early Holocene times (10,000–6000 years ago)

Postglacial sea-level rise drowned ice-age coasts in almost every part of the world, causing their inhabitants to move either inland and upslope or offshore. Along many coasts during the early Holocene, sea-level rise was accompanied by broadening of the diet range of their human inhabitants (Marín-Arroyo, 2013). This diet change may have been a response to changes in productive coastal environments and ecosystems associated with sea-level rise in addition to economic intensification linked to increases in coastal populations.

During the early Holocene, accompanied by climate changes, sea level rose about 60 m but this rise was neither monotonic nor regionally uniform (Smith et al., 2011). Sea-level transgression was instead oscillatory; there were periods of rapid rise and periods of temporary fall. For example, sea level rose about 3 m in 200 years during the 8200 BP Event (Hijma and Cohen, 2010). In coastal Portugal, this led to rapid submergence of the lower Tagus Valley that was accompanied by a massive decrease in the availability of coastal foods that forced an inland shift of coastal people who had previously occupied now-drowned coastal plains (Bicho et al., 2010). Similar events at the same time may have displaced coastal people occupying parts of the western Pacific Rim leading them to undertake deliberate voyages to settle lands beyond development of the horizon, something that may have led eventually to the maritime traditions that involved the earliest occupations of Pacific oceanic islands (Nunn, 2007b).

Middle Holocene times (6000–3000 years ago)

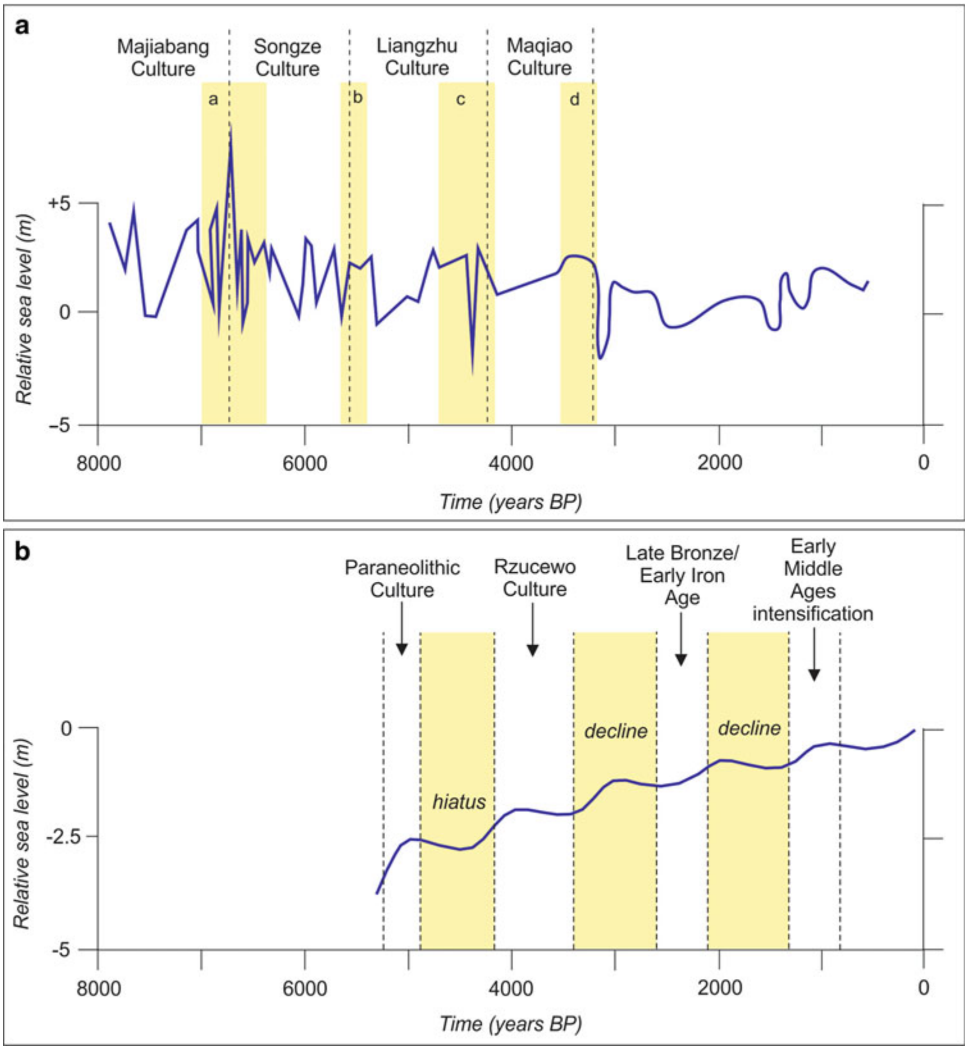
After global sea level stabilized along most coasts around 7000–5000 BP, the bioproductivity of nearshore coastal ecosystems increased sharply leading to the comparatively rapid occupation of many coasts by humans during the middle Holocene (Day et al., 2012). An example comes from the northern shoreline of New Guinea, today the largest Pacific "island" but until about 7500 years ago a promontory of Australia. Except in a few places, coastal settlement during the terminal Pleistocene and early Holocene was not possible in this part of New Guinea because of its fringe of steep cliffs plunging into deep water, but by about 6000 BP, when sea level had reached close to its present level, many of these coasts "started to evolve into rich floodplains, river deltas and lagoons" (Terrell, 2004, 605). People began to settle these areas and establish trade networks.

During the middle Holocene, sea-level fluctuations of shorter periodicity affected coastal societies in many places. Some of the most notable effects were recorded by delta communities. In the Yangtze Delta (China), mid-Holocene sea-level changes transformed coastal environments in ways that influenced wetland rice cultivation, a key driver of increasing societal complexity. A study from Tianluoshan found that, following a sea-level maximum around 7000 years ago, sea level fell and created wetlands in which Hemudu farmers could cultivate rice. Subsequent transgressions flooded these wetlands causing a drop in rice production and a consequent increase in hunting and gathering (Zheng et al., 2012). Sea-level fluctuations in this region have been linked to successive cultural collapses; larger settlements with more complex interactions were sustained at times of lower sea level but failed when the sea level rose subsequently (Figure 3a). A comparable situation has been found in the Vistula Delta (northern Europe) where four cultural phases involving changes in human lifeways that are attributable to sea-level fluctuations have been recognized in the Gdańsk area (Miotk-Szpiganowicz et al., 2010). Here, changes in the delta landscape associated with sea-level fluctuations and the alternate development/breaching of offshore barriers (protecting lowlands) saw the area utilized by agriculturalists when it was dry (often when sea level was comparatively stable) but abandoned by many people when it became flooded, those remaining being focused on fishing, sealing, and amber working (Figure 3b).

While coastal societies often respond to climate-driven sea-level changes, there are also instances where these societies have had to respond to climate changes alone. One example comes from coastal Syria where separate periods of increased aridity in the mid-late Holocene transformed productive coastal plains into hot desert (Kaniewski et al., 2008). A comparable study of the southwest coast of the Barents Sea (Norway) found that alternating warm and cool climates during the last 2000 years could be correlated with economies based mainly on cereal agriculture and fisheries, respectively (Sjögren, 2009).

Late Holocene times (<3000 years ago)

Along most of the world's coasts during the late Holocene, sea level dropped 1–2 m from its mid-Holocene high stage, causing many coastal plains and deltas to accrete and offering an advantage to resident coastal peoples. This process can be calibrated by tracing the effects on human settlements, which either remained in situ and adapted their activities to a prograding shoreline or moved as the land surface expanded. The process was never simple or easy to predict, as illustrated by an example from coastal



Coastal Settings, Figure 3 Relationship between sea-level change and cultural change. (**a**) The Yangtze Delta, eastern China (After Zhang et al., 2005; Nunn, 2007a). The Majiabang culture collapsed when high sea level caused groundwater flooding (*shaded zone a*). The Songze culture declined because of increased sea-level variability and flooding (*shaded zone b*). The Liangzhu culture collapsed as a result of sea-level increase which caused a rise in water tables and expansion of the Taihu Lakes (*shaded zone c*). Flooding linked to a high sea-level phase is also implicated in the collapse of the Maqiao culture (*shaded zone d*). (**b**) The Gulf of Gdańsk, northern Poland (After Miotk-Szpiganowicz et al., 2010), showing the variations in human occupation of the Vistula Delta that coincide with local sea-level oscillations during the later Holocene. Through creation of coastal wetlands, rising sea level is implicated in the initiation of the Paraneolithic. A later phase of sea-level rise created a large inland lagoon and extended the delta front, both of which attracted people to the area and underpinned the Rzucewo culture which later declined as sea level rose and displaced many of those people. An influx of people to the area occurred during the Late Bronze/Early Iron Age as the development of offshore barriers opened up land in the Delta that had previously been waterlogged but this land was subsequently inundated when sea level rose again. Only in the Early Middle Ages when barriers developed off the front of the Delta and large amounts of land became dry did the area rapidly become repopulated.

Peru (Figure 4). The changing resource base associated with shoreline migration during the late Holocene can also be documented in changing patterns of coastal subsistence. For example, the "mega-midden" period approximately 2000–3000 years ago along the west coast of South Africa may have been linked to environmental changes (Jerardino, 2012).

Along Mediterranean coasts, the sea-level rise of the earlier Holocene continued into the late Holocene, so that the coasts in this area show signs of continued transgression. In western Greece, for example, people at the start of the late Holocene settled close to the shore of the salt-water Messolonghi Lagoon and the adjoining freshwater Etoliko Lagoon, exploiting these diverse environments until about AD 1350 when continuing sea-level rise breached the isthmus joining both lagoons (Haenssler et al., 2013).

Within the last millennium in many parts of the world's coasts, minor perturbations of sea level occurred that in some cases led to significant responses from coastal-dwelling humans. Some of the most notable occurred as a result of rapid sea-level fall of as much as 80 cm during the AD 1300 Event (approximately AD 1250–1350) along many Pacific island coasts. This sea-level fall led to the rapid depletion of coastal foods, both onshore as a result of water-table lowering and offshore as a result of reef-surface exposure and increased lagoon turbidity. In turn, this led to conflict and, along many island coasts, the abandonment of coastal settlements in favor of others in fortifiable positions, typically upslope. Examples are known from most tropical Pacific island groups (Nunn, 2007a) with more recent work reported from Fiji and Timor (Nunn, 2012; O'Connor et al., 2012). In addition to having direct impacts on human settlement, the AD 1300 sea-level fall also caused changes to coastal landscapes that are implicated in coeval cultural changes. These include the infilling of coastal embayments and the emergence of offshore reef flats on which islands grew or could be built. Examples of the former include Tikopia (Solomon Islands) and Kawai Nui Marsh on O'ahu Island in Hawaii (USA), while the latter is exemplified by fortified Lelu Island off the coast of Kosrae (Federated States of Micronesia) and perhaps some of the artificial islands off the coast of Malaita (Solomon Islands) (Nunn, 2007a).

Tectonic disruption of coastal sites

Tectonic activity has significantly impacted the activities of coastal populations, particularly along coasts adjoining convergent lithospheric-plate boundaries. The most disruptive types of tectonic change are usually those that are abrupt and involve rapid uplift or subsidence of as much as several meters. The impacts of (associated) tsunamis often cause major problems.

The ancient Achaean city of Helike (Greece), located on a delta of the Gulf of Corinth coast, was abruptly submerged during an earthquake-tsunami in 373 BC but was subsequently uplifted, and its remains now lie buried beneath post-earthquake delta sediments (Soter and Katsonopoulou, 2011). Seismic subsidence accompanied by liquefaction caused major disruptions on at least two occasions to inhabitants of the port city of Ayla (now Aqaba, Jordan) (Al-Tarazi and Korjenkov, 2007). In the tectonically active island arcs of the southwest Pacific Ocean, many similar instances are known, the most extreme being ones where entire inhabited islands abruptly sank, in most cases probably due to an earthquake-triggered landslide along an adjoining ocean trench. Examples include the "vanished" islands of Teonimanu (Solomon Islands) and Malveveng and Tolamp (Vanuatu) (Nunn, 2009b).

Away from plate boundaries, some of the most marked coastal changes have occurred in places like Scandinavia where the land is rising as a result of isostatic rebound. The Viking-era shoreline (AD 800–1050) on the Estonian coast, for example, is now known to be 3–4 m above present sea level, emphasizing the importance in such places of understanding "the relation between a given site and the shoreline at the time when the site was used" (Ilves and Darmark, 2011, 147–148).

Conclusions and key issues

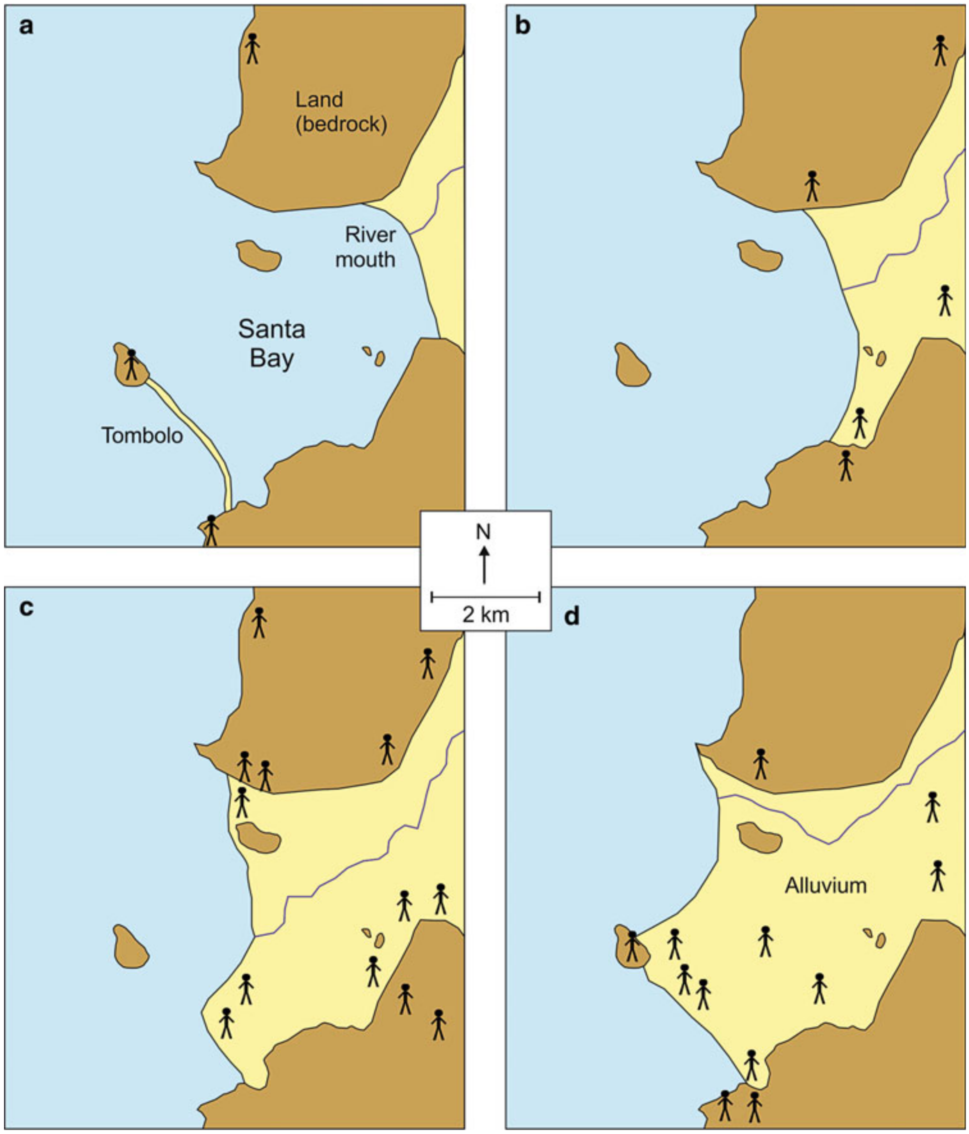
When considering the relationship between coastal settings and past human societies, there are a number of issues that remain insufficiently understood or acknowledged by many researchers. Three such issues are discussed below.

The importance of understanding coastal paleoenvironments

Despite calls to consider the effects of postglacial sea-level rise on coastal archaeological records, "many archaeologists working in coastal areas . . . have ignored such warnings" (Erlandson and Braje, 2011, 34) and continue to interpret past human-environment interactions in terms of the landscape configurations and landscape-forming processes they observe today. Such comments also extend to dynamic river deltas, such as the tendency of Egyptologists to plot the present-day rivers of the Nile Delta onto maps of the valley in the past, something that may have "misled interpretations of ancient monuments and settlements" (Hillier et al., 2007, 1011). This is hard to justify in an age when the understanding of (coastal) landscape change is so far advanced, and there are numerous examples of how this understanding can provide insights into the development of ancient societies.

Examples are illustrated above. The Lapita-age settlement at Bourewa (Fiji) was reconstructed using observations of settlement character (particularly the extent of postholes that once supported over-reef stilt houses), reef configuration, and an understanding of sea-level change to demonstrate that this settlement had extended along a submerged sand spit which emerged subsequently (see Figure 2), changing the possibilities for coastal subsistence (Nunn, 2009a). Morphological changes at the mouth of the Santa River (Peru) linked to sea-level changes explain the changes in settlement pattern shown in Figure 4 (Wells, 1992).

The locations of ancient shell middens can plot out coeval shorelines, assuming that shellfish gatherers processed their harvest just beyond the reach of high tide rather than carrying it whole back to their communities. There is no single answer. In some places, the former appears true – most shell middens (*Køkkenmødding*) in Denmark are situated along former shorelines which have been reconstructed using midden locations (Gutiérrez-Zugasti et al., 2011). In contrast, marine shell concentrations that differ little from those in coastal middens have been found 23 km inland in the Norte



Coastal Settings, Figure 4 Late Holocene growth of the Santa River Delta (Peru) showing changes in coastal settlement pattern associated with changes in shoreline configuration during the middle and late Holocene (After Wells, 1992; Nunn, 1999). Person symbol represents an archaeological site inhabited at that time. (**a**) Las Salinas Period (7000–3750 BP) shows that early settlers avoided the river valley. (**b**) Early Suchimancillo Period (1950–1750 BP) shows the initial occupation of the river mouth, targeting places where marine resources were most plentiful. (**c**) Guadalupito Period (1550–1300 BP) shows deliberate occupation of the prograding delta fringe. (**d**) Early Tambo Real Period (800–600 BP) shows more intense occupation of the delta fringe.

Chico region (coastal Peru) and 10 km inland on northern Viti Levu Island (Fiji) (Creamer et al., 2011; Robb and Nunn, 2014).

The identification of ancient shorelines and the signs of their human usage (such as boat landings) is particularly difficult in places where the Earth's crust is rebounding isostatically because this movement tends to be monotonic (only one direction: upward) rather than episodic. One approach in such places has been to use phosphate mapping to identify former shorelines, the assumption being that the human occupation of these localities resulted in an increase in surficial phosphate concentrations (from the butchering of game, the gutting of fish, human waste, burning); such a study resulted in the mapping of Österby Harbor (northwest Estonia) (Ilves and Darmark, 2011).

Imperatives for underwater archaeology

Understanding how shoreline emergence might affect coastal settings occupied by ancient humans can be obtained by investigating the sites on dry land, but the effects of shoreline submergence generally represent greater challenges. It is not simply an issue of former settlement sites being underwater but also that the material evidence associated with these sites may have been fragmented and dispersed as a result of submergence, first by the encroaching swash and backwash of wave action as the sea slowly enveloped the sites and then by further deterioration as the sites slowly sank into deeper water. For this reason, it is easier to reconstruct those sites that have been submerged only a few meters relatively recently rather than those that may be lying at water depths of 100 m or more over a lengthy interval, as is the case for most Last Glacial Maximum sites (dating from 22 to 18 ka BP) that now lie in offshore continental shelf locations. It is also important to appreciate that, once submerged, coastal settlements may become buried by sediments and even overgrown by reefs, which makes these settlements difficult to identify in many places. The danger is that they will be assumed to have been absent at a particular time, and erroneous chronologies of human history constructed as a result.

Since so much of the evidence is underwater, there are understandably few data-rich case studies of coastal societies affected by early Holocene sea-level rise. Some of the most compelling of these depend on data gathered through techniques of underwater archaeology. Underwater archaeological investigations have the potential not only to provide contexts for inferences from on-land sites (Bailey and King, 2011), but they can also demonstrate the existence of unsuspected coastal settings at particular times which in turn inform regional settlement models. An example comes from the Gulf of Maine (USA) where a slowing of postglacial sea-level rise 11,500–7500 years ago allowed development of coastal barriers and wetlands that may have attracted settlers, a finding contrary to earlier assumptions about the habitability of such formerly ice-covered coasts (Kelley et al., 2010). Perhaps the most comprehensive survey of now-submerged coastal settings occupied by a maritime society during the early Holocene comes from Doggerland (North Sea, between Britain and continental Europe) where a low-relief landscape of marshes, lakes, and wetlands dissected by rivers, now buried under marine sands, can been traced (Gaffney et al., 2009).

Debating the relative roles of natural and human processes in prehistoric coastal change

The inherent natural dynamism of coastal settings has not deterred them from being, through much of human existence, favored places for people to live, and as a result, it is not always easy to retrospectively distinguish the effects of natural and anthropogenic actions. There are many well-documented examples of ways in which humans modified coastal environments as well as examples of how coastal environmental change, linked to extraneous climate-driven changes, forced coastal dwellers to change the ways in which they lived. To judge which cause (natural or human) of an observed change in coastal societies was dominant, it is necessary to compare chronologies of both. If societal change was clearly not synchronous with possible (natural) forcing variables, then the latter is unlikely to have played a role in causing the former. But if there is demonstrable synchronicity, then a role for natural forcing should be considered possible.

Relative sea-level change is a major mechanism that could have forced adaptive change in coastal societies, and several examples were described above (see also Figure 3). Over the past decade, there has been an increasing number of case studies in which relative sea-level migration is cited as a major cause of change among coastal societies; these include tropical Pacific islands (Nunn, 2007a) and the coasts of Italy (Romano et al., 2013) and Portugal (Bicho and Haws, 2008). In many cases, the separation of natural and human causes of societal change appears almost impossible to achieve (e.g., Marín-Arroyo, 2013) given the paucity of available data.

Bibliography

Al-Tarazi, E. A., and Korjenkov, A. M., 2007. Archaeoseismological investigation of the ancient Ayla site in the city of Aqaba, Jordan. *Natural Hazards*, **42**(1), 47–66.

Amesbury, J. R., 2013. Pelagic fishing in the Mariana Archipelago: from the prehistoric period to the present. In Ono, R., Morrison, A., and Addison, D. J. (eds.), *Prehistoric Marine Resource Use in the Indo-Pacific Regions*. Canberra: Australian National University E Press, pp. 33–57. Terra Australis 39.

Anderson, A., Roberts, R., Dickinson, W., Clark, G., Burley, D., de Biran, A., Hope, G., and Nunn, P., 2006. Times of sand: sedimentary history and archaeology at the Sigatoka Dunes, Fiji. *Geoarchaeology*, **21**(2), 131–154.

Bailey, G., 2004. World prehistory from the margins: the role of coastlines in human evolution. *Journal of Interdisciplinary Studies in History and Archaeology*, **1**(1), 39–50.

Bailey, G. N., 2009. The Red Sea, coastal landscapes, and hominin dispersals. In Petraglia, M. D., and Rose, J. I. (eds.), *The Evolution of Human Populations in Arabia*. Amsterdam: Springer, pp. 15–37.

Bailey, G. N., and King, G. C. P., 2011. Dynamic landscapes and human dispersal patterns: tectonics, coastlines, and the reconstruction of human habitats. *Quaternary Science Reviews*, **30** (11–12), 1533–1553.

Bailey, G. N., and Parkington, J. (eds.), 1988. *The Archaeology of Prehistoric Coastlines*. Cambridge: Cambridge University Press.

Bailey, G. N., Flemming, N. C., King, G. C. P., Lambeck, K., Momber, G., Moran, L. J., Al-Sharekh, A., and Vita-Finzi, C., 2007. Coastlines, submerged landscapes, and human evolution: the Red Sea Basin and the Farasan Islands. *Journal of Island and Coastal Archaeology*, **2**(2), 127–160.

Balme, J., 2013. Of boats and string: the maritime colonisation of Australia. *Quaternary International*, **285**, 68–75.

Bicho, N., and Haws, J., 2008. At the land's end: marine resources and the importance of fluctuations in the coastline in the prehistoric hunter-gatherer economy of Portugal. *Quaternary Science Reviews*, **27**(23–24), 2166–2175.

Bicho, N., Umbelino, C., Detry, C., and Pereira, T., 2010. The emergence of Muge Mesolithic shell middens in central Portugal and the 8200 cal yr BP cold event. *Journal of Island and Coastal Archaeology*, **5**(1), 86–104.

Binford, L. R., 1968. Post-pleistocene adaptations. In Binford, S. R., and Binford, L. R. (eds.), *New Perspectives in Archaeology*. Chicago: Aldine, pp. 313–341.
Brysac, S. B., 2003. Letter from Germany: Atlantis of the Baltic. *Archaeology*, **56**(4), 62–66.
Burley, D. V., and Dickinson, W. R., 2001. Origin and significance of a founding settlement in Polynesia. *Proceedings of the National Academy of Sciences*, **98**(20), 11829–11831.
Cavulli, F., and Scaruffi, S., 2013. Thoughts on nomadism in Middle Holocene Oman. *Arabian Archaeology and Epigraphy*, **24**(1), 15–27.
Chen, Z., Zong, Y., Wang, Z., Wang, H., and Chen, J., 2008. Migration patterns of Neolithic settlements on the abandoned Yellow and Yangtze River deltas of China. *Quaternary Research*, **70**(2), 301–314.
Cleuziou, S., and Tosi, M., 2007. *In the Shadow of the Ancestors: The Prehistoric Foundations of the Early Arabian Civilization in Oman*. Muscat: Ministry of Heritage and Culture.
Creamer, W., Haas, J., Jakaitis, E., III, and Holguin, J., 2011. Far from the shore: comparison of marine invertebrates in midden deposits from two sites in the Norte Chico, Peru. *The Journal of Island and Coastal Archaeology*, **6**(2), 176–195.
Davidson, I., 2013. Peopling the last new worlds: the first colonisation of Sahul and the Americas. *Quaternary International*, **285**, 1–29.
Day, J. W., Jr., Gunn, J. D., Folan, W. J., Yáñez-Arancibia, A., and Horton, B. P., 2012. The influence of enhanced post-glacial coastal margin productivity on the emergence of complex societies. *Journal of Island and Coastal Archaeology*, **7**(1), 23–52.
Di Piazza, A., and Pearthree, E., 2001. An island for gardens, an island for birds and voyaging: a settlement pattern for Kiritimati and Tabuaeran, two "mystery islands" in the northern Lines, Republic of Kiribati. *Journal of the Polynesian Society*, **110**(2), 149–170.
Dickinson, W. R., 2003. Impact of mid-Holocene hydro-isostatic highstand in regional sea level on habitability of islands in Pacific Oceania. *Journal of Coastal Research*, **19**(2), 489–502.
Erlandson, J. M., and Braje, T. J., 2011. From Asia to the Americas by boat? Paleogeography, paleoecology, and stemmed points of the northwest Pacific. *Quaternary International*, **239**(1–2), 28–37.
Erlandson, J. M., Graham, M. H., Bourque, B. J., Corbett, D., Estes, J. A., and Steneck, R. S., 2007. The kelp highway hypothesis: marine ecology, the coastal migration theory, and the peopling of the Americas. *Journal of Island and Coastal Archaeology*, **2**(2), 161–174.
Field, J. S., Petraglia, M. D., and Lahr, M. M., 2007. The southern dispersal hypothesis and the South Asian archaeological record: examination of dispersal routes through GIS analysis. *Journal of Anthropological Archaeology*, **26**(1), 88–108.
Funabiki, A., Saito, Y., Phai, V. V., Nguyen, H., and Haruyama, S., 2012. Natural levees and human settlement in the Song Hong (Red River) delta, northern Vietnam. *The Holocene*, **22**(6), 637–648.
Gaffney, V. L., Fitch, S., and Smith, D. N., 2009. *Europe's Lost World: The Rediscovery of Doggerland*. York: Council for British Archaeology.
Green, R. C., 2003. The Lapita horizon and traditions – signature for one set of Oceanic migrations. In Sand, C. (ed.), *Pacific Archaeology: Assessments and Prospects (Proceedings of the International Conference for the 50th Anniversary of the First Lapita Excavation, Koné-Nouméa 2002)*. Les cahiers de l'archéologie en Nouvelle-Calédonie 15. Nouméa, Nouvelle-Calédonie: Département Archéologie, Service des Musées et du Patrimoine de Nouvelle-Calédonie, pp. 95–120.
Gutiérrez-Zugasti, I., Andersen, S. H., Araújo, A. C., Dupont, C., Milner, N., and Monge-Soares, A. M., 2011. Shell midden research in Atlantic Europe: state of the art, research problems and perspectives for the future. *Quaternary International*, **239** (1–2), 70–85.
Haenssler, E., Nadeau, M. J., Vött, A., and Unkel, I., 2013. Natural and human induced environmental changes preserved in a Holocene sediment sequence from the Etoliko Lagoon, Greece: new evidence from geochemical proxies. *Quaternary International*, **308–309**, 89–104.
Hein, C. J., FitzGerald, D. M., Milne, G. A., Bard, K., and Fattovich, R., 2011. Evolution of a Pharaonic harbor on the Red Sea: implications for coastal response to changes in sea level and climate. *Geology*, **39**(7), 687–690.
Hijma, M. P., and Cohen, K. M., 2010. Timing and magnitude of the sea-level jump preluding the 8200 yr event. *Geology*, **38**(3), 275–278.
Hillier, J. K., Bunbury, J. M., and Graham, A., 2007. Monuments on a migrating Nile. *Journal of Archaeological Science*, **34**(7), 1011–1015.
Holdaway, S. J., Fanning, P. C., Jones, M., Shiner, J., Witter, D. C., and Nicholls, G., 2002. Variability in the chronology of Late Holocene Aboriginal occupation on the arid margin of southeastern Australia. *Journal of Archaeological Science*, **29**(4), 351–363.
Ilves, K., and Darmark, K., 2011. Some critical and methodological aspects of shoreline determination: examples from the Baltic Sea region. *Journal of Archaeological Method and Theory*, **18**(2), 147–165.
Jerardino, A., 2012. Large shell middens and hunter-gatherer resource intensification along the west coast of South Africa: the Elands Bay case study. *Journal of Island and Coastal Archaeology*, **7**(1), 76–101.
Jew, N. P., Erlandson, J. M., Watts, J., and White, F. J., 2013. Shellfish, seasonality, and stable isotope sampling: $\delta^{18}O$ analysis of mussel shells from an 8,800-year-old shell midden on California's Channel Islands. *Journal of Island and Coastal Archaeology*, **8**(2), 170–189.
Kagawa, A. K., and Vitousek, P. M., 2012. The ahupua'a of Puanui: a resource for understanding Hawaiian rain-fed agriculture. *Pacific Science*, **66**(2), 161–172.
Kaniewski, D., Paulissen, E., Van Campo, E., Al-Maqdissi, M., Bretschneider, J., and Van Lerberghe, K., 2008. Middle East coastal ecosystem response to middle-to-late Holocene abrupt climate changes. *Proceedings of the National Academy of Sciences*, **105**(37), 13941–13946.
Kayanne, H., Yasukochi, T., Yamaguchi, T., Yamano, H., and Yoneda, M., 2011. Rapid settlement of Majuro Atoll, central Pacific, following its emergence at 2000 years CalBP. *Geophysical Research Letters*, **38**(20), L20405.
Kelley, J. T., Belknap, D. F., and Claesson, S., 2010. Drowned coastal deposits with associated archaeological remains from a - sea-level "slowstand": Northwestern Gulf of Maine, USA. *Geology*, **38**(8), 695–698.
Kennett, D. J., Anderson, A., and Winterhalder, B., 2006. The ideal free distribution, food production, and the colonization of Oceania. In Kennett, D. J., and Winterhalder, B. (eds.), *Behavioral Ecology and the Transition to Agriculture*. Berkeley: University of California Press, pp. 265–288.
Kirch, P. V. (ed.), 2001. *Lapita and Its Transformations in Near Oceania: Archaeological Investigations in the Mussau Islands, Papua New Guinea, 1985–88*. Berkeley: Archaeological Research Facility, University of California, Vol. 1.
Lewis, J. P., Ryves, D. B., Rasmussen, P., Knudsen, K. L., Petersen, K. S., Olsen, J., Leng, M. J., Kristensen, P., McGowan, S., and Philippsen, B., 2013. Environmental change in the Limfjord, Denmark (ca 7500–1500 cal yrs BP): a multiproxy study. *Quaternary Science Reviews*, **78**, 126–140.
Lowery, D., Jodry, M., and Stanford, D., 2012. Clovis coastal zone width variation: a possible solution for early Paleoindian

population disparity along the Mid-Atlantic coast, USA. *Journal of Island and Coastal Archaeology*, **7**(1), 53–63.
Marín-Arroyo, A. B., 2013. Human response to Holocene warming on the Cantabrian Coast (northern Spain): an unexpected outcome. *Quaternary Science Reviews*, **81**, 1–11.
Marriner, N., and Morhange, C., 2007. Geoscience of ancient Mediterranean harbours. *Earth-Science Reviews*, **80**(3–4), 137–194.
Miotk-Szpiganowicz, G., Zachowicz, J., and Uscinowicz, S., 2010. Palynological evidence of human activity on the Gulf of Gdansk coast during the late Holocene. *Brazilian Journal of Oceanography*, **58**(spe1), 1–13.
Nunn, P. D., 1999. *Environmental Change in the Pacific Basin: Chronologies, Causes, Consequences*. New York: Wiley.
Nunn, P. D., 2007a. *Climate, Environment and Society in the Pacific During the Last Millennium*. Amsterdam: Elsevier.
Nunn, P. D., 2007b. Holocene sea-level change and human response in Pacific Islands. *Earth and Environmental Science Transactions of the Royal Society of Edinburgh*, **98**(1), 117–125.
Nunn, P. D., 2009a. Geographical influences on settlement-location choices by initial colonizers: a case study of the Fiji Islands. *Geographical Research*, **47**(3), 306–319.
Nunn, P. D., 2009b. *Vanished Islands and Hidden Continents of the Pacific*. Honolulu: University of Hawai'i Press.
Nunn, P. D., 2012. Na koronivalu ni Bā: upland settlement during the last millennium in the Bā River Valley and Vatia Peninsula, northern Viti Levu Island, Fiji. *Asian Perspectives*, **51**(1), 1–21.
Nunn, P. D., and Britton, J. M. R., 2004. The long-term evolution of Niue Island. In Terry, J. P., and Murray, W. E. (eds.), *Niue Island: Geographical Perspectives on the Rock of Polynesia*. Paris: INSULA, pp. 31–74.
O'Connell, J. F., and Allen, J., 2012. The restaurant at the end of the universe: modelling the colonisation of Sahul. *Australian Archaeology*, **74**, 5–17.
O'Connor, S., McWilliam, A., Fenner, J. N., and Brockwell, S., 2012. Examining the origin of fortifications in East Timor: social and environmental factors. *Journal of Island and Coastal Archaeology*, **7**(2), 200–218.
Pope, K. O., Pohl, M. E. D., Jones, J. G., Lentz, D. L., von Nagy, C., Vega, F. J., and Quitmyer, I. R., 2001. Origin and environmental setting of ancient agriculture in the lowlands of Mesoamerica. *Science*, **292**(5520), 1370–1373.
Porat, N., Sivan, D., and Zviely, D., 2008. Late Holocene embayment infill and shoreline migration, Haifa Bay, Eastern Mediterranean. *Israel Journal of Earth Sciences*, **57**(1), 21–31.
Richter, C., Roa-Quiaoit, H., Jantzen, C., Al-Zibdah, M., and Kochzius, M., 2008. Collapse of a new living species of giant clam in the Red Sea. *Current Biology*, **18**(17), 1349–1354.
Robb, K. F., and Nunn, P. D., 2014. Changing role of nearshore-marine foods in the subsistence economy of inland upland communities during the last millennium in the tropical Pacific Islands: insights from the Bā River Valley, Northern Viti Levu Island, Fiji. *Environmental Archaeology*, **19**(1), 1–11.
Romanescu, G., 2013. Geoarchaeology of the ancient and medieval Danube Delta: modeling environmental and historical changes. A review. *Quaternary International*, **293**, 231–244.
Romano, P., Di Vito, M. A., Giampaola, D., Cinque, A., Bartoli, C., Boenzi, G., Detta, F., Di Marco, M., Giglio, M., Iodice, S., Liuzza, V., Ruello, M. R., and Schiano di Cola, C., 2013. Intersection of exogenous, endogenous and anthropogenic factors in the Holocene landscape: a study of the Naples coastline during the last 6000 years. *Quaternary International*, **303**, 107–119.
Sauer, C. O., 1962. Seashore – primitive home of man? *Proceedings of the American Philosophical Society*, **106**(1), 41–47.
Sjögren, P., 2009. Climate, cod and crops: coastal land use in the SW Barents Sea region during the past 2.5 ka. *The Holocene*, **19**(5), 703–716.
Smith, D. E., Harrison, S., Firth, C. R., and Jordan, J. T., 2011. The early Holocene sea level rise. *Quaternary Science Reviews*, **30**(15–16), 1846–1860.
Soter, S., and Katsonopoulou, D., 2011. Submergence and uplift of settlements in the area of Helike, Greece, from the Early Bronze Age to late antiquity. *Geoarchaeology*, **26**(4), 584–610.
Specht, J., 2007. Small islands in the big picture: the formative period of Lapita in the Bismarck Archipelago. In Bedford, S., Sand, C., and Connaughton, S. P. (eds.), *Oceanic Explorations: Lapita and Western Pacific Settlement*. Canberra: Australian National University ePress, pp. 51–70.
Stančikaitė, M., Daugnora, L., Hjelle, K., and Hufthammer, A. K., 2009. The environment of the Neolithic archaeological sites in Šventoji, Western Lithuania. *Quaternary International*, **207**(1–2), 117–129.
Stanley, J.-D., Warne, A. G., and Schnepp, G., 2004. Geoarchaeological interpretation of the Canopic, largest of the relict Nile delta distributaries, Egypt. *Journal of Coastal Research*, **20**(3), 920–930.
Stark, M. T., 2006. Early mainland Southeast Asian landscapes in the first millennium A.D. *Annual Review of Anthropology*, **35**, 407–432.
Szabó, K., and Amesbury, J. R., 2011. Molluscs in a world of islands: the use of shellfish as a food resource in the tropical island Asia-Pacific region. *Quaternary International*, **239**(1–2), 8–18.
Terrell, J. E., 2002. Tropical agroforestry, coastal lagoons, and Holocene prehistory in Greater Near Oceania. In Yoshida, S., and Matthews, P. J. (eds.), *Vegeculture in Eastern Asia and Oceania*. Osaka: Japan Center for Area Studies, National Museum of Ethnology, pp. 195–216.
Terrell, J. E., 2004. The 'sleeping giant' hypothesis and New Guinea's place in the prehistory of Greater Near Oceania. *World Archaeology*, **36**(4), 601–609.
Von Glasow, R., Jickells, T. D., Baklanov, A., Carmichael, G. R., Church, T. M., Gallardo, L., Hughes, C., Kanakidou, M., Liss, P. S., Mee, L., Raine, R., Ramachandran, P., Ramesh, R., Sundseth, K., Tsunogai, U., Uematsu, M., and Zhu, T., 2013. Megacities and large urban agglomerations in the coastal zone: interactions between atmosphere, land, and marine ecosystems. *Ambio*, **42**(1), 13–28.
Weisler, M. I., 1996. Taking the mystery out of the Polynesian "mystery" islands: a case study from Mangareva and the Pitcairn Group. In Davidson, J. M., Irwin, G., Leach, B. F., Pawley, A., and Brown, D. (eds.), *Oceanic Culture History: Essays in Honour of Roger Green*. Dunedin North: New Zealand Journal of Archaeology Special Publication, pp. 615–629.
Weisler, M. I., Bolt, R., and Findlater, A., 2010. Prehistoric fishing strategies on the makatea island of Rurutu. *Archaeology in Oceania*, **45**(3), 130–143.
Wells, L. E., 1992. Holocene landscape change on the Santa Delta, Peru: impact on archaeological site distributions. *The Holocene*, **2**(3), 193–204.
Zhang, Q., Zhu, C., Liu, C. L., and Jiang, T., 2005. Environmental change and its impacts on human settlement in the Yangtze Delta, P.R. China. *Catena*, **60**(3), 267–277.
Zheng, Y. F., Sun, G. P., and Chen, X. G., 2012. Response of rice cultivation to fluctuating sea level during the Mid-Holocene. *Chinese Science Bulletin*, **57**(4), 370–378.

Cross-references

Alluvial Settings
Geomorphology
Harbors and Ports, Ancient
Landscape Archaeology
Paleoenvironmental Reconstruction
Paleoshores (Lakes and Sea)
Shell Middens
Submerged Continental Shelf Prehistory

COLLUVIAL SETTINGS

Charles A. I. French
Department of Archaeology and Anthropology,
University of Cambridge, Cambridge, UK

Introduction

Colluvium, or hillwash, is both an erosive deposit and a preserving medium for buried surfaces. The term encompasses slope deposits moved by shallow surface flow (or slope wash) or by mass movement (or creep or slide). Colluvium is soil- and/or sediment-derived material that accumulates on lower slopes. It is poorly sorted and heterogeneous, composed of any size grade from clay to coarse sand plus rock rubble, and can be up to several meters thick (Waters, 1992, 230–232; Selby, 1993, 243). Bedding and stratification are often poor and particularly hard to identify in the field (as opposed to in thin section), and colluvium may also contain a variety of artifact inclusions brought down from upslope. Colluvium may occur any place that possesses more than two degrees of slope, even beneath woodland (Imeson et al., 1980).

Hillwash can be generated by a variety of processes, of which devegetation and agriculture are two of the main instigators. Consequently, colluvial sequences frequently contain a record of human activities and reflect anthropogenic impacts on landscapes. Colluvium also has the ability to distort, bury, and preserve past landscapes, especially over the last 10,000 years. How and why deposits are laid down and subsequently modified, and at what rate, are central issues in geoarchaeology. Detailed information can be gleaned from colluvial sequences through the use of good field recording, particle size analysis, associated soil micromorphological and molluscan studies, and appropriate use of dating techniques. Thus, hillwash is a valuable resource in archaeology and geoarchaeology, but an understanding of its formation, depositional processes, and chronology is required.

This entry examines and illustrates the formation and depositional factors causing hillwash in a variety of landscape settings in order to demonstrate its importance in the interpretation of past land use and human activities and exemplify these through a number of case studies from around the world.

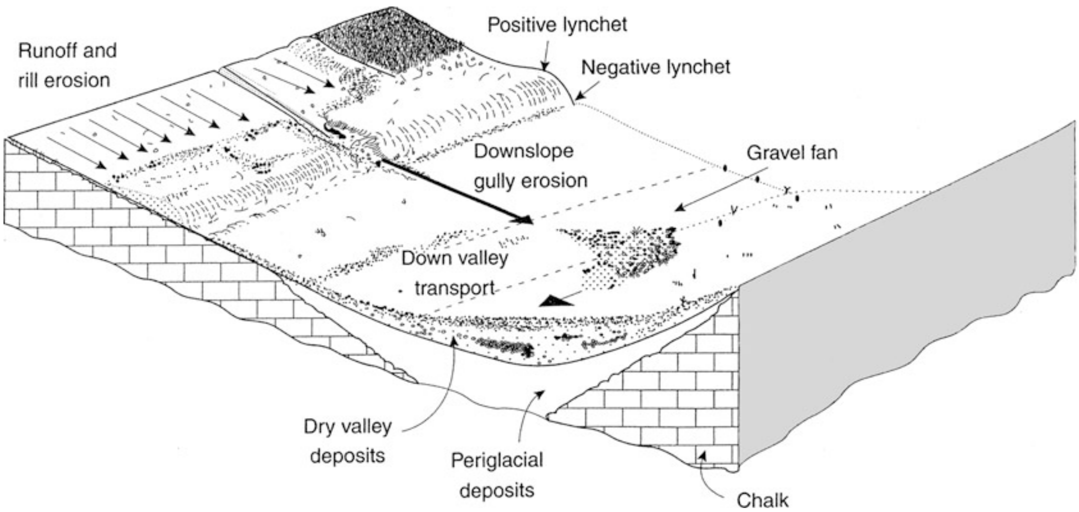
Formation of hillwash

Slope processes regularly lead to soil erosion, transport, and redeposition of soils and sediments in valley situations (Figure 1), and they are therefore involved in both the alteration and the preservation of archaeological sites and landscapes. Soil/sediment movement may range from rapid to slow and intermittent to gradual. Every situation is exacerbated by the degree and character of the slope, topography, hydrology, vegetation cover, rainfall amounts and frequencies, and the nature of human activities on the land.

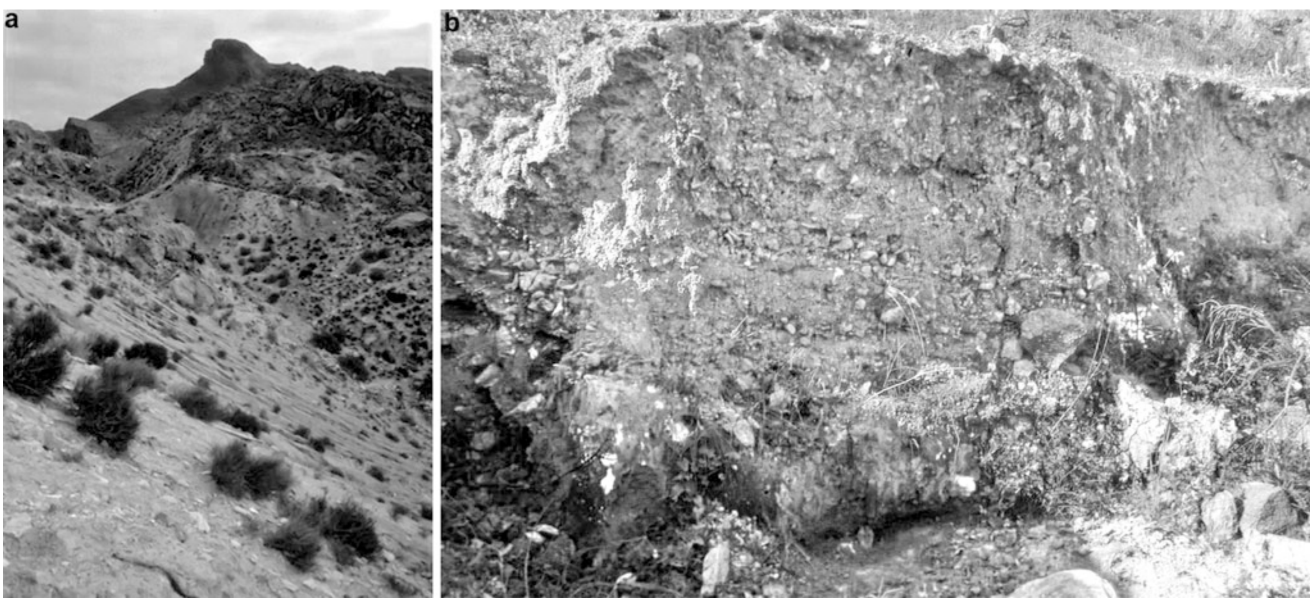
There are two major types of soil/sediment movement on slopes related to process: (1) slope, hill, and rainwash and (2) mass wasting. The former group generates colluvial deposits, and the latter group is associated more with solifluction and debris flow deposits. Mass movement involves the rapid downslope movement of rock and soil debris from a rupture surface and/or shear plane, which is usually controlled by the intact strength of the soil and/or subsoil (Statham, 1979; Statham, 1990). It is a fast movement, often as a single erosive event, with stability quickly returning. A rockfall after a freeze-thaw episode and slab failure on a rock face are typical examples. In the Sierra Cabrera mountains of southeastern Spain, for example, rock debris and gully erosion regularly shear off material from the upper slopes above the Barranco de Gatas, which falls onto the first agricultural terraces below as rubbly fans (French et al., 1998) (Figure 2a, b).

Slow and/or seasonal slope processes produce slow downslope translocations of soil debris as soil creep or colluviation (Statham, 1979; Statham, 1990). These can be near continuous, seasonal, or random in occurrence, they can affect small or large areas of slope, and they can occur anywhere. This type of movement can result from frost heave in soils, periglacial conditions and solifluction, rainsplash impact, and saturation and/or waterlogging, often aggravated in arable areas by the farming regime. For example, massive soil creep can result from the saturation and cultivation of bare slopes, as is seen in Bosnia today (Figure 3a), or in sandy hillwash deposits accumulating at the base of slopes in later prehistoric to historic times adjacent to the grand Saxon burials at Sutton Hoo, Suffolk (Carver, 1998; French, 2005) (Figure 3b). Often, such areas of eroded soil accumulation are easily mapped from the air and ground-truthed through auger survey and test pitting, as exemplified by the mapping of later Holocene hillwash deposits in the dry valleys of the upper Allen valley of Dorset (French et al., 2007, 23–35) (Figure 4).

Slide or water flow processes such as overland flow on slopes and alluviation in floodplains produce variable rates of deposition. Overland flow is particularly influenced by slope angle, soil, and vegetation type and in turn by the amount of rainwater splash impact (Selby, 1993), as well as human impacts. During flow, the sediment load tends to decrease with time. Overland flow occurs when either the infiltration capacity of the soil is exceeded either during high intensity rainfall or during the rapid melting of snow. Grains of c. 0.5 mm in diameter are the most easily moved, whereas smaller and larger grains require a much higher threshold velocity. Grains are not redeposited until very low flow velocities are reached (Morgan, 1979). With reference to the Spanish example, past and recent colluvial fans and overland flow deposits comprising meters of coarse silt and very fine sand-size, calcitic marl material were regularly observed in out-of-use agricultural terraces and dry valleys of the Barranco de Gatas (French et al., 1998) (Figure 5a). Moreover, the removal of natural vegetation, the presence of



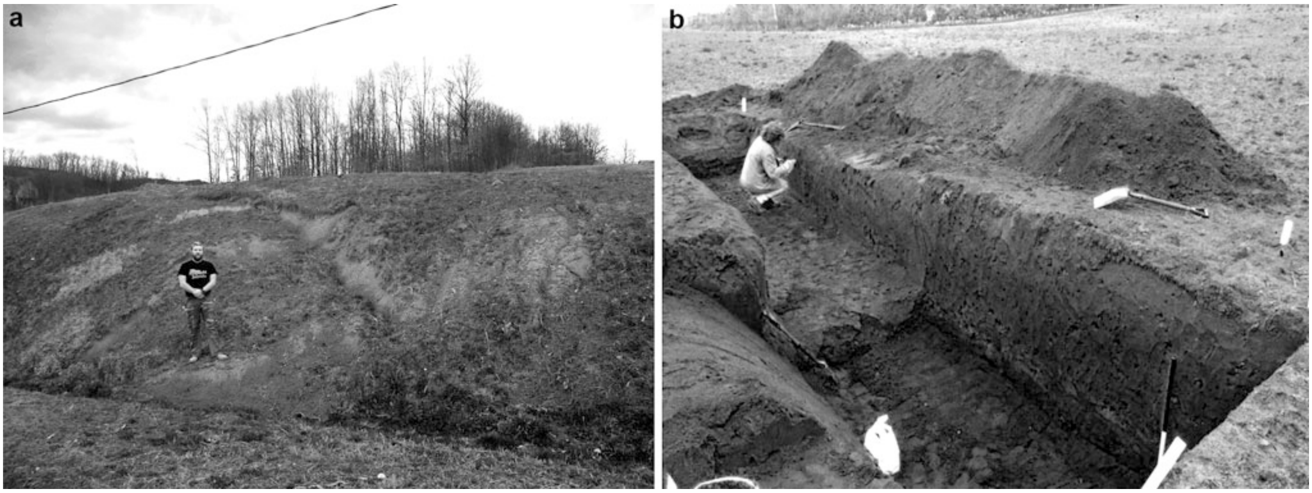
Colluvial Settings, Figure 1 Schematic cross section of a colluviated valley landscape (After Allen, 1988; Goldberg and Macphail, 2006: Figure 4.4).



Colluvial Settings, Figure 2 (**a**) Gully erosion on steep, bare slopes above Fuente Alamo, southern Spain. (**b**) Soil and rock debris accumulation in an abandoned agricultural terrace in the Barranco de Gatas, Sierra Cabrera, southern Spain.

steep slopes, and extensive past agricultural exploitation for wheat crops, coupled with increasing aridification since the second millennium BC, have exacerbated the susceptibility of soils and subsoils of this region to erode downslope (Castro et al., 1999).

The presence of colluvium is often directly related to human activities in the landscape and particularly to arable agriculture. Bare arable land and ongoing cultivation regularly result in the direct displacement of soil downslope and its redeposition at the base of the slope as colluvium or within the adjacent floodplain as alluvium (Figure 1). The exposure of soil/sediment particles and aggregates to the elements leads to further physical breakup of soil structure. Add water and a slope angle of greater than two degrees, and soil movement downslope can take place; if vegetation cover is removed, even greater soil erosion may occur (Figures 2a and 5b) more quickly and more often (Mücher, 1974; Kwaad and Mücher, 1979; Selby, 1993, 106–122). Disturbances due to people or animals can easily produce gullying and soil erosion as well



Colluvial Settings, Figure 3 (**a**) Recent colluvial slumping near Prijedor, in central Bosnia. (**b**) Historic and later prehistoric sand hillwash overlying a disturbed acidic sandy brown earth in the Deben valley associated with the Bronze Age settlement site and Saxon ship burials at Sutton Hoo, Suffolk, England.

as the accumulation of eroded soil/sediment downslope, often against boundaries (such as field banks and hedges) to form lynchets. For example, browsing of pigs in present-day cork oak woodland in northern Sicily has led to gully erosion and soil transport downslope within a few months (Figure 5b). Evidence of past soil erosion and accumulation is often seen associated with prehistoric field boundaries such as the later prehistoric "Celtic" fields and lynchets on the chalk downlands of southern England (Evans, 1972, 316; Limbrey, 1975, 188–189) (Figure 6), or at the base of slopes in the Aguas valley of southern Spain associated with the Bronze Age settlement and agriculture upslope of Las Pilas (French et al., 1998: Figure 13.5).

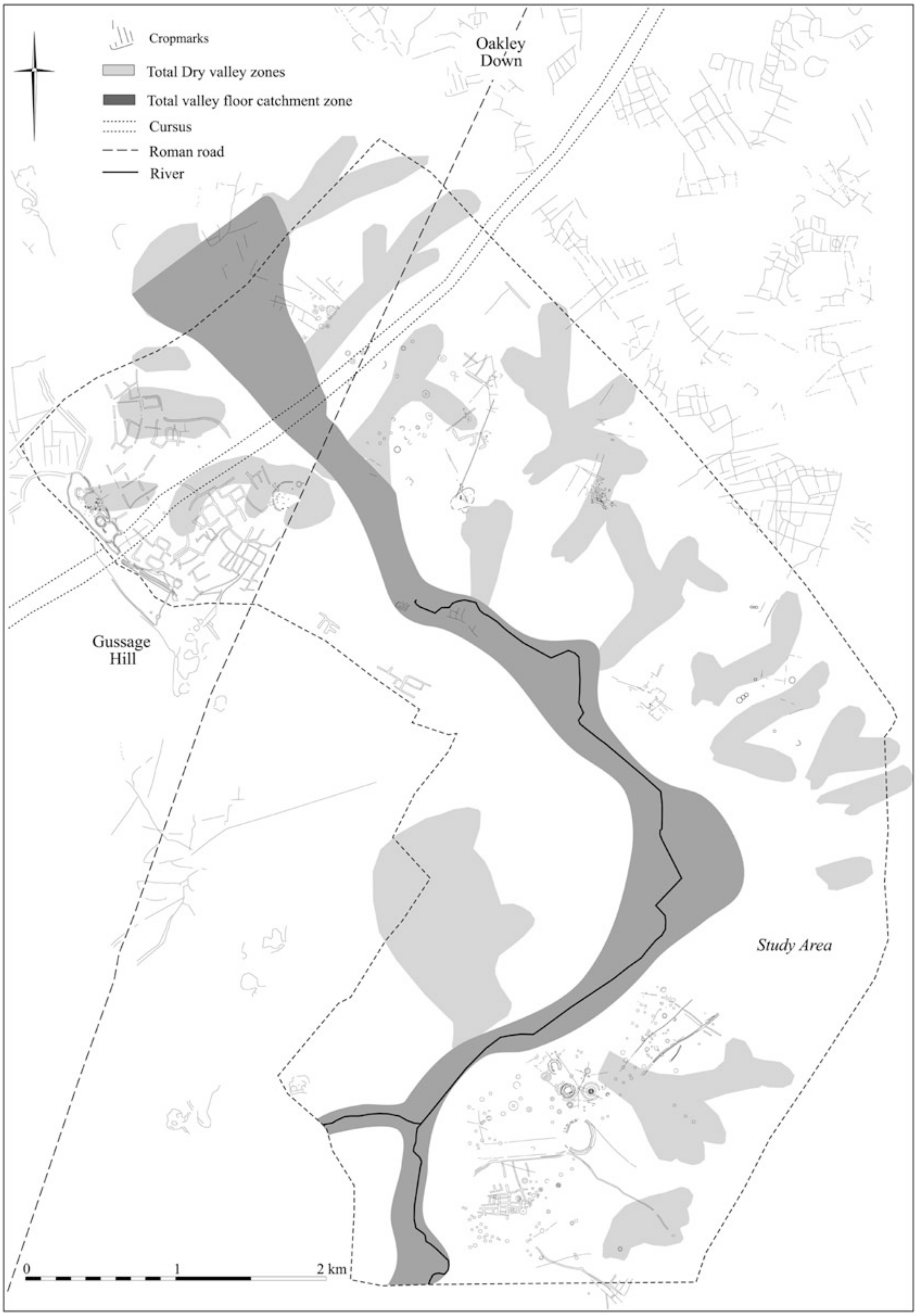
Different amounts and rates of saturation will also affect the threshold at which soil movement occurs as well as the speed and distance of travel. For example, if a soil requires only 50 % saturation to become mobile (or plastic), shear will occur more quickly and more often, dependent, of course, on the nature of the vegetation cover and degree of slope; if a soil becomes saturated at 90 % moisture content, however, it will be less susceptible to shear and colluvial displacement downslope (Selby, 1993, 56–63). Plowing and overcropping can lead to the depletion of not just essential minerals for plant or crop growth, but the destruction of soil structure, thus making a soil more prone to destabilization and downslope movement. Soil texture also affects its movement, with fine sandy and coarse silty soils being much more susceptible to destabilization than well-structured silty clay loam soils (Selby, 1993, 106–122). This will be compounded when vegetative cover is removed or the soil is physically disturbed by plowing or animal trampling.

In addition to these formation factors, it is also worth considering the ecological concepts of thresholds of stability/instability (Butzer, 1982; Allen, 1992). Change in just one factor in a landscape, or a combination of several factors, might be sufficient to cause instability in a soil system. This could be as simple as an individual thunderstorm event on a dry, bare soil, or it could be a combination of factors, such as an unstructured sandy soil fabric on overgrazed and degraded grassland with 20° of slope and a prolonged rainy spell that causes a catastrophic shear and slumping of soil downslope. Each response will be governed partly by climatic, environmental, human, and land-use factors as much as the diverse pattern and different magnitudes of individual valley responses.

Rates of colluvial movement

Rates of soil/sediment movement downslope can vary enormously over time, and modern experimental observations are often the only real analogue providing indications of the volume of soil moved versus soil texture, time, slope, vegetation, and land use (Table 1). For example, debris flow in southern Spain can produce up to several meters of accumulation in one event such as from a single thunderstorm (French, 2003, p. 207, Figure 13.7). This is because there is (1) almost no moisture infiltration into the soil/substrate, (2) a high erodibility index, and (3) a lack of vegetative cover, all leading to very high rates of runoff (Thornes and Gilman, 1983). Colluvial soil creep can be continuous, seasonal, or random. Its formation can be exacerbated by steeper slope gradients, bare soil surfaces, soil moisture exceeding its infiltration capacity, soil/sediment texture, rainfall and temperature regime, and human activities such as plowing.

Rates of colluviation have been observed in many modern landscapes, and these data provide a good idea of the



Colluvial Settings, Figure 4 Colluvial accumulations in the upper Allen valley mapped against the terrain and archaeological record.

Colluvial Settings, Figure 5 (**a**) Overland flow colluvial soil creep and gullying of unmaintained terrace systems in the Barranco de Gatas, Sierra Cabrera, southern Spain. (**b**) Soil slumping and wastage in open cork oak woodland caused by pigs, near Troina in north-central Sicily.

Colluvial Settings, Figure 6 Later prehistoric field system banks or lynchets (raised former field boundaries consequent upon colluvial accumulation against hedgerows) at Abbotsbury, Dorset, England.

speed and volumes of material that can be moved downslope under particular conditions. For example, under coppiced oak/beech woodland on loessic (or windblown) soils in Luxembourg, as much as 6 cm of soil per 100 years had accumulated (Kwaad and Mücher, 1979; Imeson et al., 1980). Observed rates of soil loss can vary from 0.0045 g per square meter per year for areas of moderate relief under natural conditions to 0.045 kg per square meter per year for steep relief and rates of 4.5–45 kg per square meter per year on agricultural land (Young, 1969). A major controlling factor is the angle of slope; the total transport caused by sheet erosion has been observed to increase sixfold as the slope angle increased from flat to 25° (Moseley, 1973).

Factors that influence soil erosion and its severity are rainfall, runoff, wind, soil type, slope angle, and the amount of vegetative cover, both on localized and regional scales. Erosion tends to reach a maximum in temperate,

Colluvial Settings, Table 1 Examples of measured rates of soil erosion from experimental plots in the southeastern United States (After Kirkby, 1969)

Type of vegetation cover	% runoff	Soil loss (mm per year)
Oak forest	0.8	0.008
Grass pasture	3.8	0.03
Oak woodland	7.9	0.1
Bare abandoned land	48.7	24.4
Cultivated, with rows along the contour	47.0	10.6
Cultivated, with rows downslope	58.2	29.8

semiarid areas with a mean annual rainfall of c. 250–350 mm per year (Langbein and Schumm, 1958). In more humid areas, and as one moves from drier to wetter environments, rates of erosion initially decrease rapidly to the point (at c. 600 mm per year) at which total vegetation cover is established; rates change little thereafter. For example, in the northern Cambridgeshire region, where the annual rainfall varies between 500 and 600 mm (Burton, 1981), the greater vegetative cover tends to counteract the erosive effect of greater rainfall. In contrast, the Rio Puerco of New Mexico experiences very low rainfall of 200 mm per year that occurs during thunderstorms; land use associated with intensive livestock grazing has contributed to conditions resulting in massive river incision of up to 11–12 m over approximately the past 120 years (French et al., 2009).

Rainsplash is probably the most important detaching agent and contributes considerably to runoff. Splash back following raindrop impact on a level surface has been observed to move stones 4 mm in diameter up to 20 cm, while 2 mm sized stones can be displaced up to 40 cm, and even smaller stones up to 150 cm (Kirkby, 1969). Short-lived, intense, and prolonged storms of low intensity have the greatest erosive effect (Morgan, 1979; French et al., 2009).

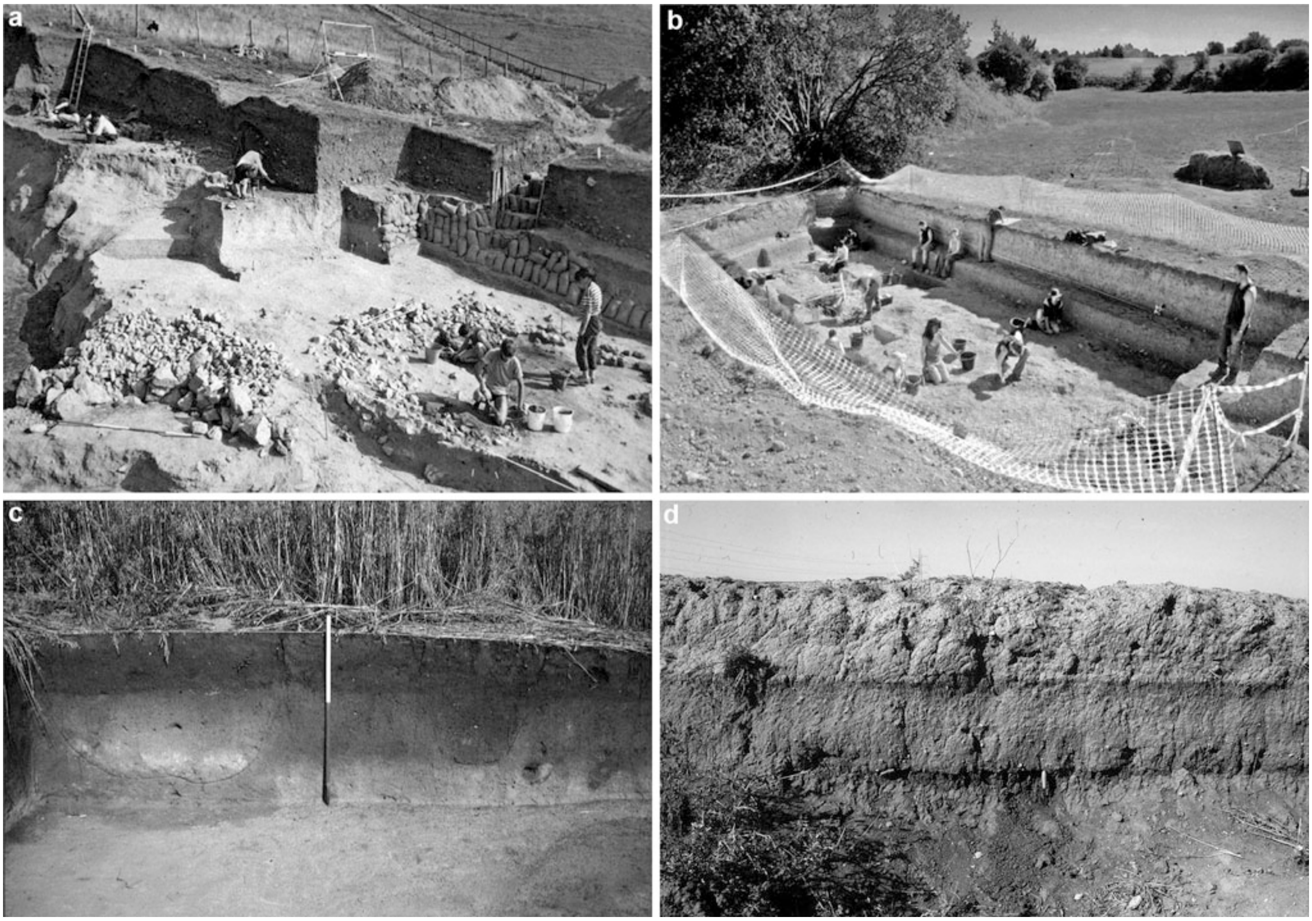
Surface runoff or overland flow occurs on slopes when the soil's infiltration capacity is exceeded (Kirkby, 1969). Overland flow transports soil particles detached by rainsplash, often creating distinct gullies or channels (Figure 2a). It has been suggested that overland flow covers two-thirds or more of hillsides in a drainage basin during the peak period of a storm (Horton, 1945). Grains of c. 0.5 mm in diameter (coarse silt or very fine- and fine-sized sand) are most easily moved, whereas both smaller and larger grains require a much higher threshold velocity. Clay tends to resist detachment (Farmer, 1973). Grains are not redeposited until very low flow velocities are reached (Morgan, 1979). Subsurface soil water flow erodes possibly only 1 % of the total material from a hillside (Roose, 1970).

The resistance of soil to detachment and transport depends on the steepness of slope, vegetative cover, and disturbance by humans. It also varies with soil texture, aggregate stability, shear strength, infiltration capacity, and the organic and chemical components (Selby, 1993, 106–122). The least resistant particles are silts and fine sands. Soils with a low shear strength or low cohesiveness are susceptible to mass movement, as are those with a low infiltration rate and low organic matter content (Morgan, 1979).

The effect of slope is to increase erosion with increasing slope angle (Kirkby, 1969). Numerous forces such as gravity, frost heave, rainsplash, soil texture, and the lack of vegetative cover all help to produce erosion on slopes. The amount of vegetative cover has a considerable effect on the susceptibility of soil to erosion. Its effectiveness in reducing downslope erosion depends on the height, density, and continuity of the canopy or ground/root cover. Both forest and dense grass are more or less equally effective at reducing erosion. Vegetation intercepts rainfall and reduces the velocity of runoff. Mean annual soil loss on bare ground can be as much as 100 times the volume of loss from dense grass-covered ground under the same environmental conditions (Morgan, 1979), and soil loss on vegetated slopes can be reduced by 10–30 % (Horton, 1945). Moreover, conversion of forest to arable land will dramatically increase erosion by up to 200-fold (Wolman, 1967). Thus, vegetation is a critical factor, and the removal of plant cover especially on slopes can considerably enhance the potential for erosion by overland flow, slope wash, or some other mode of transport.

Hillwash deposition may frequently be discontinuous, with many pauses in the gradual sediment buildup. These episodic sequences are not always easily detectable in the field, but they may exhibit "standstill" horizons that usually show some organic accumulation and a degree of soil formation if the hiatus was of sufficient duration to allow some pedogenesis to occur. A good example of this is at Brean Down, Somerset, where a basal Neolithic paleosol was buried by a sequence of hillwash and blown sand episodes that were interrupted by standstill phases with turf development and several later prehistoric, Bronze Age occupations (Bell, 1990) (Figure 7a). This type of sequence lends itself to good dating through both archaeological and artifact associations as well as radiocarbon and/or luminescence techniques (see below).

Variable hillwash accumulations are common. For example, Bronze Age settlement and agriculture on the sand-dominated soils at Sutton Hoo have led to over 1.5 m of undifferentiated soil hillwash accumulation downslope in the adjacent Deben valley (Figure 3b). In contrast, two major episodes of hillwash accumulation, one predating and the other postdating the Romano-British period, were found within the center of the late Neolithic henge at Durrington Walls, Wiltshire (Figure 7b). Associated with this was a major erosive interval affecting the calcitic rendzina soil material that was found in old paleochannels of the Avon valley at Durrington Walls (French et al., 2012). Also, a mixture of thick deposits of soil and rock debris is known to

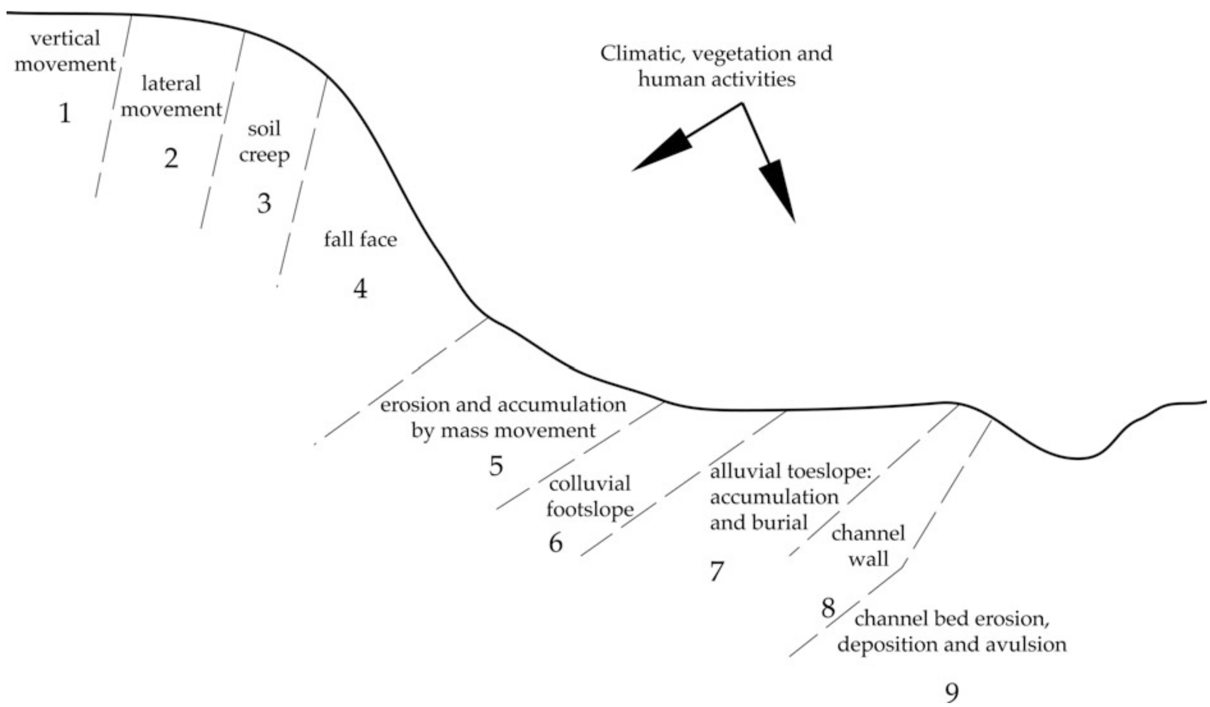


Colluvial Settings, Figure 7 (**a**) Repeated paleosol, hillwash, and blown sand deposits of Bronze Age to medieval times at Brean Down, Somerset, England (Bell, 1990: Figure 32). (**b**) Two major episodes of rendzina soil erosion and colluvial accumulation bracketing an incipient rendzina soil of the Roman period (at the level of the tape measure) within the interior of the late Neolithic henge at Durrington Walls, Wiltshire, England. (**c**) Episodic pre-Roman loessic soil erosion and paleosol formation at Erd in the Benta valley, central Hungary. (**d**) Two phases of soil development in post-Neolithic hillwash deposits at Bet el-Kowmani in the Dhamar highlands of Yemen.

aggrade episodically as colluvium in dry valleys of Sussex in southeastern England from at least the Beaker period, e.g., at Newbarn Combe on the Isle of Wight (Allen, 1992: Figure 4.2; Bell, 1992: Figure 3.3; Boardman, 1992). Near Szazhalombatta in the lower Benta tributary of the Danube, there were three episodic periods of hillwash accumulation – in the Bronze Age, Iron Age, and medieval times – each on an old land surface represented by a paleosol indicating a lengthy period of stability (French, 2010a) (Figure 7c). Several episodic phases of hillwash accumulation were also observed burying Neolithic paleosols in the Dhamar highlands of Yemen (French, 2003, 224–234; Wilkinson, 2005) (Figure 7d).

Nine-unit land-surface erosion model and catena sequence

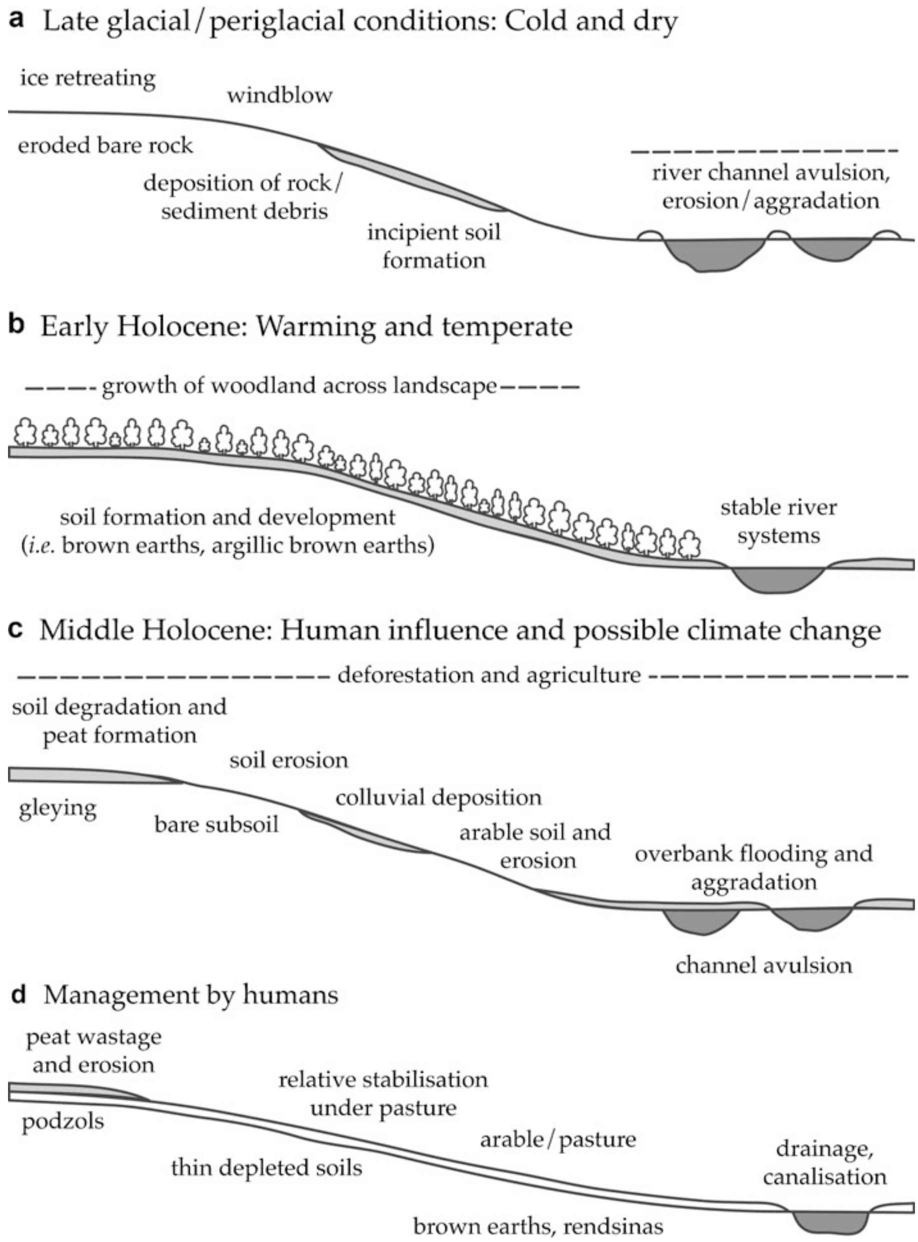
The use of Dalrymple et al.'s (1968) nine-unit land-surface erosion model (Figure 8) is a good way of envisaging erosion and landscape change both across and within a valley landscape. It allows the visualization of every part of a landscape at whatever scale of investigation is being used. This model creates an idealized cross section through one-half of a valley, from the watershed boundary at the highest point of the valley to the river channel below. If this model is then combined with the catena concept (see below), both geomorphological processes and soil formation and change can be seen in combination. When archaeological distributions by time period are overlaid and related to these geomorphological contours, they form the beginnings of a two-dimensional model of landscape development, which when extended and viewed in plan allows the use of digital terrain and geographical information system models to analyze landscape change in three dimensions through time. A case study of this type of work in the upper Allen valley of the chalk downlands of southern England (French et al., 2007) is discussed below.



Colluvial Settings, Figure 8 Dalrymple's nine-unit land-surface model (After Dalrymple et al., 1968).

A catena (based on the Latin word for chain) is a sequence of soils that forms along the course of a particular slope, usually over one parent material (Limbrey, 1975, 83; Goldberg and Macphail, 2006, 63). The differences between the soils that form a catena are generally related to their varied positions on the slope and their drainage characteristics. These factors produce changes in soil properties from the upper elevation members to the lower elevation members of the catena, and they can also create a sequence of modifications to catenas through time – i.e., a paleo-catena (Figure 9). Thus, a catena is a sequence of soil profiles appearing in regular succession with similar and differing morphological features over a uniform lithology.

The nine-unit land-surface model combines slope aspect, degree of slope, erosion, and soil forming processes (Dalrymple et al., 1968) (Figure 8). The uppermost unit (1) exhibits less than 1° of slope; it is characterized by pedogenic processes with vertical subsurface movement and is often associated with waterlogging or severe denudation. Below that, unit 2 exhibits 2–4° of slope, with both chemical and mechanical eluviation (or removal) by lateral subsurface water movement. Unit 3 is the upper part of the fall face with 35–45° of slope, and it is characterized by bare rock surfaces, sheet erosion, soil creep, and terracette formation. Unit 4 is the lower and steeper part of the fall face with 45–64+ degrees of slope, which is characterized by physical and chemical erosion leading to much bare rock, rock falls, and slides. Unit 5 is the mid-slope zone with 26–35° of slope, surface and subsurface water action, transport by mass movement, terracette formation, and both the removal and accumulation of soil and sediment material. Unit 6 is effectively the colluvial footslope zone, where there is subsurface water action, redeposition of material by mass movement, and some surface wash as colluvium, as well as transport further downslope in the form of hillwash and down valley in the form of alluvium. This colluvium may be laminated, nonlaminated, or massive, and it often accumulates on a buried soil that may or may not be truncated. Unit 7 in the floodplain is characterized by alluvial deposition as well as downstream water movement containing colluvially derived material as alluvium. Unit 8 in the active floodplain exhibits channel avulsion and erosion, bank slump, and fall. Unit 9 is the active channel itself, with bed transport down valley, as well as periodic aggradation and erosion. Obviously, not all units and slope angles will be applicable to every landscape encountered during fieldwork, but the model gives foreknowledge as to where areas of denudation, transformation, and burial may be occurring within a valley complex. As a corollary, it will also provide a good indicator of where buried soils and land surfaces may survive and where buried waterlogged deposits may be found intact for paleo-vegetational and land-use reconstruction. These data can also be used to inform a universal soil loss equation (USLE) to model landscape change through time (Wischmeier et al., 1971; Wischmeier and Smith, 1978; Ayala and French, 2005; French, 2010b) (see below).



Colluvial Settings, Figure 9 Hypothetical series of paleo-catena sequences for southern England in the late glacial-Holocene.

Methods of analysis

Two main approaches have been used to study colluvial processes, namely, (1) observation and recording in the field backed up by (2) experimental studies in the field and laboratory. More recently, a much wider repertoire of techniques has emerged for routine use. Good field description and mapping of soil and colluvial deposits is an essential starting point for appraising soil erosion in any landscape. Aerial photography and remote sensing methods such as LIDAR are essential tools (Wilson, 2000; Donoghue, 2001; Bewley et al., 2005), perhaps even geophysical survey and the use of ground-penetrating radar (GPR) to determine sediment thicknesses (Clark, 2000; Gaffney and Gator, 2003) accompanied by systematic augering profiles and test pitting to ascertain depths and characteristics of the erosion/soil complex (French, 2003; French et al., 2007). Test pitting allows bulk sampling from the section face for molluscan studies (Allen, 1992). It also permits block samples to be taken for soil micromorphological analysis (Courty et al., 1989; French, 2003), as well as small bulk sampling for particle size analysis, pH, carbonates, loss on ignition, and magnetic susceptibility (Allen and Macphail, 1987; Canti, 1995; Bertran and Texier, 1999; English Heritage, 2004;

Goldberg and Macphail, 2006), while permitting the recording of stone content and its orientation, recovery of artifacts for relative dating, and sampling and sieving to retrieve charcoal for radiocarbon assay (French, 2003; Goldberg and Macphail, 2006). If any clear horizon differences exist, or there are perceptible old land surfaces in evidence, optically stimulated luminescence (or OSL) dating can also be used effectively to provide sequence dating (Grün, 2001). Finally, both laboratory and field experimental data from known present-day landscape scenarios on different soil and geological types need to be compiled and used for comparison as analogues for potential rates of slope erosion under known conditions (Kwaad and Mücher, 1979; Evans, 1992).

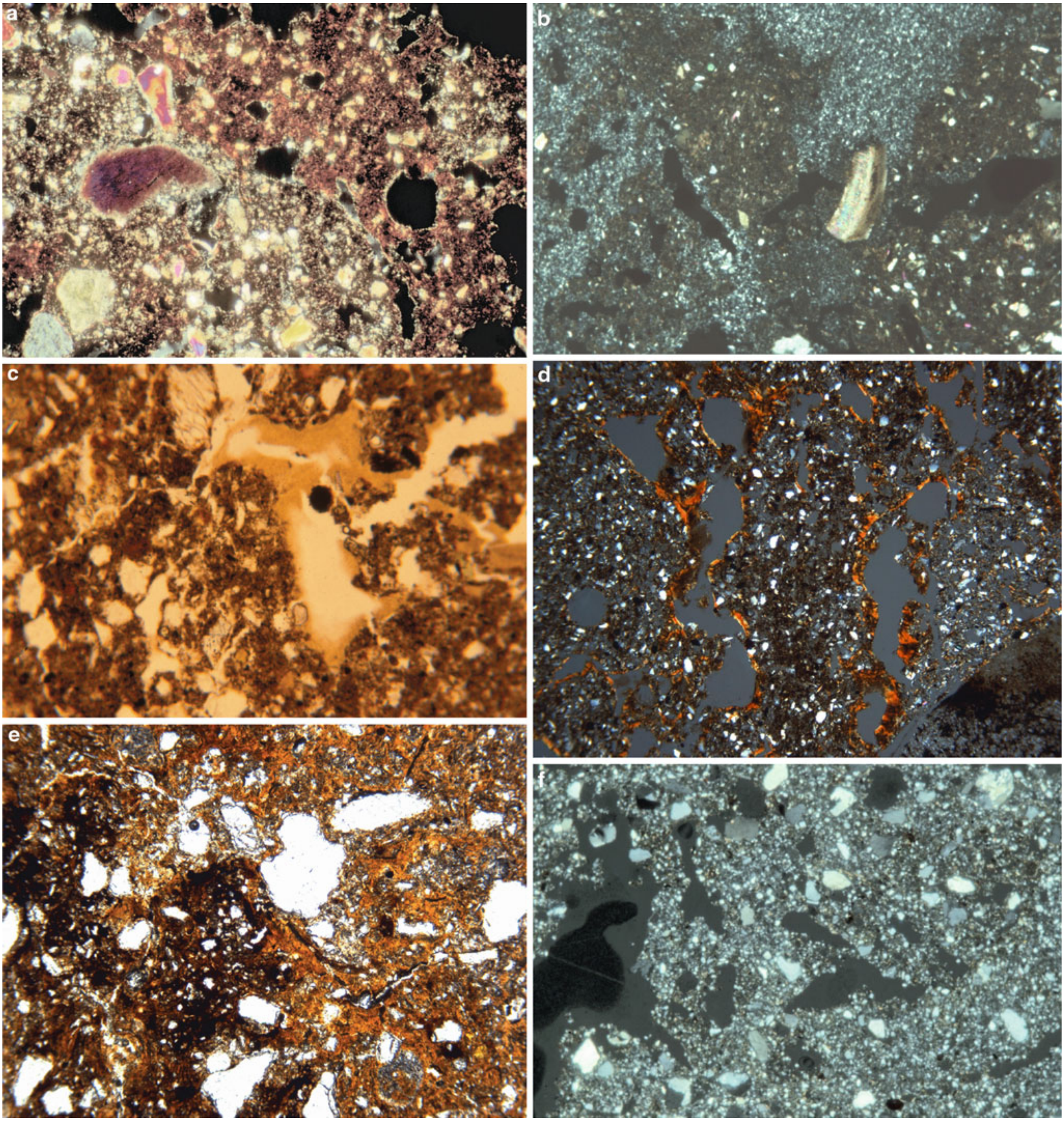
Once hillwash has been recognized and recorded in the field as a deposit, micromorphological analysis can then play a role in providing corroborative evidence as part of a mixed method approach (Courty et al., 1989; Canti, 1995; English Heritage, 2004). Different slope processes may generate similar types of micromorphological features, and consequently, it is essential to use a suite of criteria and methodological approaches as itemized above, including macromorphological features and granulometry, for corroboration and a more reliable interpretation (Mücher et al., 2010, p. 37). Moreover, there has not been a large amount of micromorphological research work done on slope deposits (Mücher, 1974; Mücher and Morozova, 1983; Bertran and Texier, 1999). Nonetheless, features such as (1) mixed, juxtaposed, and heterogeneous fabrics (Figure 10a, b), often as pedo-relict aggregates; (2) fresh and/or unoriented subrounded rock fragments; (3) sharply bounded nodules; (4) surface or mud crusts, often fragmented and in all orientations; (5) silty clay coatings; (6) infillings and intercalations in the void/channel space between soil peds (Figure 10c–e); (7) fabrics depleted of fine material (Figure 10f); and (8) anthropogenic inclusions are all common indicators of colluvial deposits (Mücher, 1974; Goldberg and Macphail, 2006, 44–45; Fedoroff et al., 2010, 641–645; Kuhn et al., 2010, 228–230; Mücher et al., 2010). Micromorphology can also distinguish quite well between in situ soils and redeposited soils/sediments, and it will recognize fine laminations in colluvial deposits as well as various postdepositional processes. Crucially, micromorphology can identify different types of clay coatings, which can be associated with hillwash processes, often the result of rainsplash impact on bare soil surfaces, such as oriented pure clays (Figure 10c), dusty impure silty clay coatings with weak to moderate striae (Figure 10d), silty clay intercalations (Figure 10e), and dirty or very speckled clay coatings with weak orientation (Bolt et al., 1980; Goldberg and Macphail, 2006, 44–45; Kuhn et al., 2010).

Studies of molluscan assemblages may also be used to help define different localized environments within a valley catchment and to recognize cyclical land-use regimes (Allen, 1988; Allen, 1992). Usually, the molluscan faunas in hillwash reflect arable activity and are generally depleted assemblages with a narrow species range (Bell, 1983). Any temporary hiatuses or standstill horizons can reflect grassland or incipient soil formation (Kerney et al., 1964; Allen, 1992). Occasionally palynological (Scaife, 1984) and micromorphological analyses (Macphail et al., 1990; Macphail, 1992) can aid in the interpretation of land use and activities represented in the colluvial stratigraphy.

Once the formation, age, depths, and spatial extent of colluvial deposits have been determined, and the deposits have been mapped and set within their geological, soil, and vegetational contexts, it then becomes possible to model past and present landscape change. This involves using the tools of geographical information system (GIS) and the universal soil loss equation (USLE) and erodibility factor (K) (Wischmeier et al., 1971; Wischmeier and Smith, 1978) to model erosion in a landscape, as well as dynamic people-landscape interactions in the archaeological record (Kwan and Lee, 2004; Conolly and Lake, 2006; Wainwright, 2008; French, 2010b). For example, in the Troina valley of north-central Sicily, USLE and GIS modeling techniques were used to model the potential impact of Roman agriculture on the erosion record (Ayala and French, 2005). The study suggested that greater clearance for winter pasture land may have been the major driving force causing intensified soil erosion. Other recent studies (Barton et al., 2004; Barton et al.,2010) have effectively employed both computational applications (USLE and GIS) and developed them further using a Geographic Resource Analysis and Support System (GRASS) to model socio-ecological interactions. This type of approach will not only enable visualization of a landscape's erosion record, but it will also allow (1) comparisons to be made between long-term landscape dynamics and the archaeological record as well as (2) further testing using different landscape settings and different scales of human activity.

Dating

Dating of colluvial sequences is rarely easy. Artifacts such as pottery and lithics are often included in eroded soils as hillwash deposits, but of course, they may be inverted or mixed in depositional terms, making them unreliable indicators of the age of any slope deposit. They should certainly not be used on their own without other corroborative data and dating methods. But, it is a different matter if standstill zones with in situ archaeological materials are found within a colluvial sequence, such as the Bronze Age and later sequence at Brean Down (Bell, 1990) (Figure 7a). This type of episodic deposition and standstill sequence allows dates "after which" (*terminus post quem*) and relative dating of the main phases in the profile based on their archaeological components. In addition, it is sometimes possible to make



Colluvial Settings, Figure 10 Photomicrographs of colluvial features in thin section: (**a**) Juxtaposed fabrics from the Neolithic paleosol at the Etton causewayed enclosure, Cambridgeshire, England (frame width = 4.5 mm; cross-polarized light). (**b**) Fine calcitic sandy clay loam with calcitic/gypsic infills from Gatas, Spain (frame width = 4.5 mm; cross-polarized light). (**c**) Pure clay as channel infills/linings in a pre-Iron Age paleosol under hillwash at Ribat Amran, Yemen (frame width = 4.5 mm; plane-polarized light). (**d**) Pure to dusty clay linings of the soil fabric of barrow mound 41, Wyke Down, Dorset, England (frame width = 4.5 mm; cross-polarized light). (**e**) Clay intercalations in a pre-Bronze Age paleosol under hillwash near Stonehenge, Wiltshire, England (frame width = 4.5 mm; plane-polarized light). (**f**) Bronze Age, depleted, poorly sorted, fine sandy loam hillwash fabric, Barranco de Gatas, Spain (frame width = 4.5 mm; cross-polarized light).

relative linkages to other regional events recorded in associated environmental, archaeological, and/or historical records that are already dated. For example, Nile flood records in pharaonic Egypt (Adamson et al., 1980; Brown, 1997, 6–7), extreme weather conditions such as those occurring during the Little Ice Age of northwestern Europe in the AD 1500s (Lamb, 1979), the huge eruption of Santorini in the Bronze Age (*c*. 1625–1645) (Aitken et al., 1988), biostratigraphic correlation with well-dated pollen records in the study area (Brown 1997, 47), and tree-ring series and ice core sequences can provide proxy dated records of major erosive and climatic events for some parts of the world.

Radiocarbon dating is an ideal method (Taylor, 2001), but it depends upon an organic component – such as charcoal, wood, bone, or other humic substance – being incorporated within the eroded material or stratified within any standstill horizons. There might nevertheless still be problems related to how the organic matter selected for dating was introduced into the eroded sediments, and uncontrolled taphonomic processes could produce inverted or otherwise erroneous dates. The reliability of any dated sequence is improved by obtaining numerous dates. For example, in the Dhamar Highlands of Yemen, sets of radiocarbon dates from the fifth millennium BC were obtained from the humic content of buried soils associated with several pre- and post-Neolithic hillwash sequences (Wilkinson, 2005), and in the central Rio Puerco valley of New Mexico, some 125 radiocarbon dates were obtained from charcoal in one reach of the Rio Puerco and its associated tributary Arroyo Tapia in order to date the 11 m thick colluvial/alluvial/buried soil sequence from about 5750 BC to the present (French et al., 2009).

Luminescence dating is another excellent technique, now increasingly being used because it yields much better accuracy than it has previously and is widely applicable (Aitken, 1997; Grün, 2001). Thermoluminescence dating (or TL) may be used on pottery and burnt flint, and optically stimulated luminescence (or OSL) works well for sedimentary sequences, especially where there are clear contacts of eroded material with buried land surfaces. For example, early Neolithic TL dates were obtained from pottery in hillwash deposits associated with two Neolithic sites in the Troina valley of north-central Sicily, and Bronze Age, Roman, and late medieval OSL dates were determined from the various stop/start alluvial profiles in the associated river floodplain (Ayala and French, 2005; R. Bailey, pers. comm.). Recent work on the Channel Island of Herm has successfully employed OSL dating techniques to chart the episodic deposition of windblown sands between about 1200 BC and AD 1600 on buried soils of Neolithic age (Bailiff et al., 2014; Scarre and French 2013).

In sum, the combination of dated archaeological associations and environmental sequences and the use of radiocarbon and/or OSL techniques are essential tools with which to date colluvial sequences. OSL dating should revolutionize future understanding of dynamic landscape change where there are repeated episodes of soil erosion and deposition.

Importance and conclusion

Colluvial deposits and the land surfaces and paleosols that they bury represent valuable resources for archaeological, paleoenvironmental, and landscape interpretation. They inform us not only about landscape development and land use in the past but also (1) the variability of human and natural impacts on valley systems, (2) the links between past and current processes of land degradation, and (3) possibly even associated climate change. The use of new techniques, such as micromorphology, OSL dating, and GIS-based modeling tools, is beginning to transform our understanding of the chronology of many colluvial sequences, as well as our ability to relate these deposits to human-land interactions through time.

Acknowledgments

I would like to thank Drs Mike Allen and Richard Macphail and Professor Paul Goldberg for permission to use Figure 1 and Professor Martin Bell for Figure 7a.

Bibliography

Adamson, D. A., Gasse, F., Street, F. A., and Williams, M. A. J., 1980. Late Quaternary history of the Nile. *Nature*, **288**(5786), 50–55.

Aitken, M. J., 1997. Luminescence dating. In Taylor, R. E., and Aitken, M. J. (eds.), *Chronometric Dating in Archaeology*. New York: Plenum, pp. 183–216.

Aitken, M. J., Michael, H. N., Betancourt, P. P., and Warren, P. M., 1988. The Thera eruption: continuing discussion of the dating. *Archaeometry*, **30**(1), 165–182.

Allen, M. J., 1988. Archaeological and environmental aspects of colluviation in south-east England. In Groenman-van Waateringe, W., and Robinson, M. (eds.), *Man-Made Soils*. Oxford: British Archaeological Reports. International Series, Vol. 410, pp. 67–92.

Allen, M. J., 1992. Products of erosion and the prehistoric land use of the Wessex Chalk. In Bell, M. G., and Boardman, J. (eds.), *Past and Present Soil Erosion*. Oxford: Oxbow. Oxbow Monograph, Vol. 22, pp. 37–52.

Allen, M. J., and Macphail, R. I., 1987. Micromorphology and magnetic susceptibility studies: their combined role in interpreting archaeological soils and sediments. In Fedoroff, N., Bresson, L.-M., and Courty, M.-A. (eds.), *Micromorphologie des sols/Soil Micromorphology*. Plaisir: Association Française pour l'Etude du Sol, pp. 669–676.

Ayala, G., and French, C., 2005. Erosion modeling of past land-use practices in the Fiume di Sotto di Troina valley, north-central Sicily. *Geoarchaeology*, **20**(2), 149–167.

Bailiff, I. K., French, C., and Scarre, C. 2014. Application of luminescence dating and geomorphological analysis to the study of landscape evolution, settlement and climate change on the Channel island of Herm. *Journal of Archaeological Science*, **41**, 890–903.

Barton, C. M., Bernabeu, J., Aura, J. E., Garcia, O., Schmich, S., and Molina, L., 2004. Long-term socioecology and contingent landscapes. *Journal of Archaeological Method and Theory*, **11**(3), 253–295.

Barton, C. M., Ullah, I. I., and Mitasova, H., 2010. Computational modeling and Neolithic socioecological dynamics: a case

study from Southwest Asia. *American Antiquity*, **75**(2), 364–386.
Bell, M. G., 1983. Valley sediments as evidence of prehistoric land-use on the South Downs. *Proceedings of the Prehistoric Society*, **49**, 119–150.
Bell, M. G., 1990. *Brean Down Excavations 1983–1987*. London: English Heritage. Historic Buildings and Monuments Commission Archaeological Report, Vol. 15.
Bell, M. G., 1992. The prehistory of soil erosion. In Bell, M. G., and Boardman, J. (eds.), *Past and Present Soil Erosion*. Oxford: Oxbow. Oxbow Monograph, Vol. 22, pp. 21–36.
Bell, M. G., and Boardman, J. (eds.), 1992. *Past and Present Soil Erosion*. Oxford: Oxbow. Oxbow Monograph, Vol. 22.
Bertran, P., and Texier, J.-P., 1999. Facies and microfacies of slope deposits. *Catena*, **35**(2–4), 99–121.
Bewley, R. H., Crutchley, S. P., and Shell, C. A., 2005. New light on an ancient landscape: lidar survey in the Stonehenge World Heritage Site. *Antiquity*, **79**(305), 636–647.
Boardman, J., 1992. Current erosion on the South Downs: implications for the past. In Bell, M. G., and Boardman, J. (eds.), *Past and Present Soil Erosion*. Oxford: Oxbow. Oxbow Monograph, Vol. 22, pp. 9–19.
Bolt, A. J. J., Mücher, H. J., Sevink, J., and Verstraten, J. M., 1980. A study on loess-derived colluvia in southern Limbourg (The Netherlands). *Netherlands Journal of Agricultural Science*, **28**(2), 110–126.
Brown, A. G., 1997. *Alluvial Geoarchaeology: Floodplain Archaeology and Environmental Change*. Cambridge: Cambridge University Press.
Burton, R. G. O., 1981. *Soils in Cambridgeshire II*. Harpenden: Soil Survey. Soil Survey Record No. 69.
Butzer, K. W., 1982. *Archaeology as Human Ecology*. Cambridge, UK: Cambridge University Press.
Canti, M. G., 1995. A mixed-method approach to geoarchaeological analysis. In Barham, A. J., and Macphail, R. I. (eds.), *Archaeological Sediments and Soils: Analysis, Interpretation and Management*. London: Institute of Archaeology, University College, London, pp. 183–190.
Carver, M. O. H., 1998. *Sutton Hoo: Burial Ground of Kings?* London: British Museum Press.
Castro, P. V., Chapman, R. W., Gili, S., Lull, V., Micó, R., Rihuete, C., Risch, R., and Sanahuja, M. E., 1999. Agricultural production and social change in the Bronze Age of southeast Spain: the Gatas Project. *Antiquity*, **73**(282), 846–856.
Clark, A. J., 2000. *Seeing Beneath the Soil: Prospecting Methods in Archaeology*, 2nd edn. London: Routledge.
Conolly, J., and Lake, M. W., 2006. *Geographical Information Systems in Archaeology*. Cambridge: Cambridge University Press. Cambridge Manuals in Archaeology.
Courty, M.-A., Goldberg, P., and Macphail, R. I., 1989. *Soils and Micromorphology in Archaeology*. Cambridge: Cambridge University Press.
Dalrymple, J. B., Blong, R. J., and Conacher, A. J., 1968. A hypothetical nine unit landsurface model. *Zeitschrift für Geomorphologie*, **12**, 60–76.
Donoghue, D. N. M., 2001. Remote sensing. In Brothwell, D. R., and Pollard, A. M. (eds.), *Handbook of Archaeological Sciences*. Chichester: Wiley, pp. 555–563.
English Heritage, 2004. *Geoarchaeology: Using Earth Sciences to Understand the Archaeological Record*. Swindon: English Heritage.
Evans, J. G., 1972. *Land Snails in Archaeology*. London: Seminar Press.
Evans, R., 1992. Erosion in England and Wales – the present the key to the past. In Bell, M. G., and Boardman, J. (eds.), *Past and Present Soil Erosion*. Oxford: Oxbow. Oxbow Monograph, Vol. 22, pp. 53–66.
Farmer, E. E., 1973. Relative detachability of soil particles by simulated rainfall. *Soil Science Society of America Journal*, **37**(4), 629–633.
Fedoroff, N., Courty, M.-A., and Guo, Z., 2010. Palaeosoils and relict soils. In Stoops, G., Marcelino, V., and Mees, F. (eds.), *Interpretation of Micromorphological Features of Soils and Regoliths*. Amsterdam: Elsevier, pp. 623–662.
French, C. A. I., 2003. *Geoarchaeology in Action: Studies in Soil Micromorphology and Landscape Evolution*. London: Routledge.
French, C. A. I., 2005. Micromorphological studies. In Carver, M. O. H., and Sutton, H. (eds.), *A Seventh-Century Princely Burial Ground and Its Context*. London: The British Museum Press, pp. 384–389. 363–379.
French, C. A. I., 2010a. The palaeo-environments of Bronze Age Europe. In Earle, T., and Kristiansen, K. (eds.), *Organizing Bronze Age Societies: The Mediterranean, Central Europe, and Scandinavia Compared*. Cambridge: Cambridge University Press, pp. 34–56.
French, C. A. I., 2010b. People, society, and landscapes. *Science*, **328**(5977), 443–444.
French, C. A. I., Passmore, D., and Schulte, L., 1998. Geomorphology and edaphic factors. In Castro, P. V., Chapman, R. W., Gili, S., Lull, V., Micó, R., Rihuete, C., Risch, R., and Sanahuja, M. E. (eds.), *Aguas Project: Palaeoclimatic Reconstruction and the Dynamics of Human Settlement and Land Use in the Area of the Middle Aguas (Almería), in the South-East of the Iberian Peninsula*. Luxembourg: European Commission, pp. 45–52.
French, C. A. I., Lewis, H., Allen, M. J., Green, M., Scaife, R., and Gardiner, J., 2007. *Prehistoric Landscape Development and Human Impact in the Upper Allen Valley, Cranborne Chase, Dorset*. Cambridge: McDonald Institute for Archaeological Research.
French, C. A. I., Periman, R., Cummings, L. S., Hall, S., Goodman-Elgar, M., and Boreham, J., 2009. Holocene alluvial sequences, cumulic soils and fire signatures in the middle Rio Puerco basin at Guadalupe Ruin, New Mexico. *Geoarchaeology*, **24**(5), 638–676.
French, C. A. I., Scaife, R. G., Allen, M. J., Pearson, M. P., Pollard, J., Richards, C., Thomas, J., and Welham, K., 2012. Durrington Walls to West Amesbury by way of Stonehenge: a major transformation of the Holocene landscape. *Antiquaries Journal*, **92**, 1–36.
Gaffney, C. F., and Gator, J., 2003. *Revealing the Buried Past: Geophysics for Archaeologists*. Stroud: Tempus.
Goldberg, P., and Macphail, R. I., 2006. *Practical and Theoretical Geoarchaeology*. Oxford: Blackwell.
Grün, R., 2001. Trapped charge dating (ESR, TL, OSL). In Brothwell, D. R., and Pollard, A. M. (eds.), *Handbook of Archaeological Sciences*. Chichester: Wiley, pp. 47–62.
Horton, R. E., 1945. Erosional development of streams and their drainage basins; a hydrophysical approach to quantitative morphology. *Bulletin of the Geological Society of America*, **56**(3), 275–370.
Imeson, A. C., Kwaad, F. J. P. M., and Mücher, H. J., 1980. Hillslope processes and deposits in forested areas of Luxembourg. In Cullingford, R. A., Davidson, D. A., and Lewin, J. (eds.), *Timescales in Geomorphology*. Chichester: Wiley, pp. 31–42.
Kerney, M. P., Brown, E. H., and Chandler, T. J., 1964. The Late-Glacial and Post-Glacial history of the chalk escarpment near Brook, Kent. *Philosophical Transactions of the Royal Society Series B, Biological Sciences*, **248**(745), 135–204.
Kirkby, M. J., 1969. Erosion by water on hillslopes. In Chorley, R. J. (ed.), *Water, Earth and Man*. London: Methuen, pp. 229–238.
Kühn, P., Aguilar, J., and Miedema, R., 2010. Textural pedofeatures and related horizons. In Stoops, G., Marcelino, V., and Mees,

F. (eds.), *Interpretation of Micromorphological Features of Soils and Regoliths*. Amsterdam: Elsevier, pp. 217–250.
Kwaad, F. J. P. M., and Mücher, H. J., 1979. The evolution of soils and slope deposits in the Luxembourg Ardennes near Wiltz. *Geoderma*, **17**(1), 1–37.
Kwan, M.-P., and Lee, J., 2004. Geovisualization of human activity patterns using 3D GIS: a time-geographic approach. In Goodchild, M. F., and Janelle, D. G. (eds.), *Spatially Integrated Social Science*. Oxford: Oxford University Press, pp. 48–66.
Lamb, H. H., 1979. Climatic variation and changes in the wind and oceanic circulation: the Little Ice Age in the northeast Atlantic. *Quaternary Research*, **11**(1), 1–20.
Langbein, W. B., and Schumm, S. A., 1958. Yield of sediment in relation to mean annual precipitation. *Transactions of the American Geophysical Union*, **39**(6), 1076–1084.
Limbrey, S., 1975. *Soil Science and Archaeology*. London: Academic.
Macphail, R. I., 1992. Soil micromorphological evidence of ancient soil erosion. In Bell, M. G., and Boardman, J. (eds.), *Past and Present Soil Erosion*. Oxford: Oxbow. Oxbow Monograph, Vol. 22, pp. 197–215.
Macphail, R. I., Courty, M.-A., and Gebhardt, A., 1990. Soil micromorphological evidence of early agriculture in north-west Europe. *World Archaeology*, **22**(1), 53–69.
Morgan, R. P. C., 1979. *Soil Erosion*. London: Longman.
Moseley, M. P., 1973. Rainsplash and the convexity of badland divides. *Zeitschrift für Geomorphologie Supplementband*, **18**, 10–25.
Mücher, H. J., 1974. Micromorphology of slope deposits: the necessity of a classification. In Rutherford, G. K. (ed.), *Soil Microscopy*. Kingston: The Limestone Press, pp. 553–566.
Mücher, H. J., and Morozova, T. D., 1983. The application of soil micromorphology in Quaternary geology and geomorphology. In Bullock, P., and Murphy, C. P. (eds.), *Soil Micromorphology*. Berkhamsted: A. B. Academic Publishers, pp. 151–194.
Mücher, H. J., van Steijn, H., and Kwaad, F., 2010. Colluvial and mass wasting deposits. In Stoops, G., Marcelino, V., and Mees, F. (eds.), *Interpretation of Micromorphological Features of Soils and Regoliths*. Amsterdam: Elsevier, pp. 37–48.
Roose, E. J., 1970. Importance relative de l'érosion, du drainage oblique et vertical dans la pédogenèse actuelle d'un sol ferrallitique de moyenne Côte d'Ivoire. *Cahiers ORSTROM, série Pedologie*, **8**(4), 469–482.
Scaife, R. G., 1984. *Gallibury Down, Isle of Wight – Pollen Analysis of a Bronze Age Downland Palaeosol*. London: English Heritage. Ancient Monuments Laboratory Report, Vol. 4240.
Scarre, C., and French, C. A. I., 2013. The palaeogeography and Neolithic archaeology of Herm in the Channel Islands. *Journal of Field Archaeology*, **38**(1), 4–20.
Selby, M. J., 1993. *Hillslope Materials and Processes*, 2nd edn. Oxford: Oxford University Press.
Statham, I., 1979. *Earth Surface Sediment Transport*. Oxford: Clarendon.
Statham, I., 1990. Slope processes. In Goudie, A. (ed.), *Geomorphological Techniques*, 2nd edn. London: Unwin Hyman, pp. 225–259.
Taylor, R. E., 2001. Radiocarbon dating. In Brothwell, D. R., and Pollard, A. M. (eds.), *Handbook of Archaeological Sciences*. Chichester: Wiley, pp. 23–34.
Thornes, J. B., and Gilman, P., 1983. Potential and actual erosion around archaeological sites in southeast Spain. In de Ploey, J. (ed.), *Rainfall Simulation, Runoff and Soil Erosion*. Cremlingen: Catena Verlag. Catena Supplement, Vol. 4, pp. 91–113.
Wainwright, J., 2008. Can modelling enable us to understand the rôle of humans in landscape evolution? *Geoforum*, **39**(2), 659–674.
Waters, M. R., 1992. *Principles of Geoarchaeology: A North American Perspective*. Tuscon: The University of Arizona Press.
Wilkinson, T. J., 2005. Soil erosion and valley fills in the Yemen Highlands and southern Turkey: integrating settlement, geoarchaeology, and climate change. *Geoarchaeology*, **20**(2), 169–192.
Wilson, D. R., 2000. *Air Photo Interpretation for Archaeologists*. Stroud: Tempus.
Wischmeier, W. H., and Smith, D. D., 1978. *Predicting Rainfall Erosion Losses: A Guide to Conservation Planning*. Washington, DC: US Department of Agriculture. Agricultural Handbook, Vol. 537.
Wischmeier, W. H., Johnson, C. B., and Cross, B. V., 1971. A soil erodibility nomograph for farmland and construction sites. *Journal of Soil and Water Conservation*, **26**(5), 189–193.
Wolman, M. G., 1967. A cycle of sedimentation and erosion in urban river channels. *Geografiska Annaler Series A, Physical Geography*, **49**(2–4), 385–395.
Young, A., 1969. Present rate of land erosion. *Nature*, **224**(5222), 851–852.

Cross-references

Alluvial Settings
Archaeological Stratigraphy
Geomorphology
Geophysics
Mass Movement
Optically Stimulated Luminescence (OSL) Dating
Paleoenvironmental Reconstruction
Remote Sensing in Archaeology

COSMOGENIC ISOTOPIC DATING

Ari Matmon
The Institute of Earth Sciences, The Hebrew University, Jerusalem, Israel

Definition

Calculating the age of rock and sediment surfaces according to their concentration of cosmogenic isotopes.

Cosmogenic isotopes, such as ^{26}Al, ^{10}Be, ^{21}Ne, ^{36}Cl, ^{14}C, and ^{3}H, are produced in the atmosphere as *meteoric nuclides* and at the surface of the Earth as in situ *terrestrial cosmogenic nuclides*, or TCNs, by interaction between cosmic particles and target atoms (Gosse and Phillips, 2001; Dunai, 2010). The production of TCN depends on geographic location and altitude.

Cosmic particles are attenuated so that they produce cosmogenic isotopes only within the upper several meters of the Earth's crust. Therefore, the concentration of TCN in rock or sediment is a good indication that it spent time close to or at the surface.

The concentration of TCN in a sample can be interpreted in two end-member ways (Bierman, 1994):

1. Representing a constant erosion rate (E) over a long time ($t \approx \infty$)

$$N = \frac{P}{\lambda + \frac{E}{\Lambda/\rho}} \tag{1}$$

2. Representing exposure time at the surface and assuming $E \approx 0$

$$N = \frac{P}{\lambda}\left(1 - e^{-\lambda t}\right) \tag{2}$$

where
N = concentration in atoms g^{-1} quartz
t = exposure time in years
λ = decay constant (yr^{-1})
E = erosion rate in cm yr^{-1}
P = production rate at depth in atoms $year^{-1}$ g^{-1} quartz
Λ = attenuation length (g cm^{-2})
ρ = overburden rock density (g cm^{-3})

The choice of calculating an erosion rate or exposure age depends on the context. Relevant examples are the calculation of exposure ages of relict surfaces, such as glacially carved surfaces, or of boulders that have experienced very little erosion. On the other hand, erosion rate calculations are suitable for landforms that are continuously being eroded due to tectonic uplift.

Quartz is commonly used in TCN dating. It is widely available in rocks and sediments, its chemistry is simple, and the analytical extraction of TCN is relatively straightforward.

Cosmogenic isotopes can also be used to date the age at which a sediment was buried, for example, in an alluvial terrace, glacial till, or in caves (Granger, 2006). The $^{26}Al/^{10}Be$ ratio in buried quartz grains, which were previously exposed, will decrease at an exponential rate due to the different half-lives of the two isotopes:

$$\frac{N_{26}}{N_{10}} = \left(\frac{N_{26}}{N_{10}}\right)_0 e^{-t_{burial}\left(\frac{1}{\tau_{26}} - \frac{1}{\tau_{10}}\right)} \tag{3}$$

where

N_{26}, N_{10} = measured concentrations of ^{26}Al and ^{10}Be (atoms g^{-1} quartz)
$(N_{26}/N_{10})_0$ = initial $^{26}Al/^{10}Be$ at burial
t_{burial} = time since burial
τ_{26}, τ_{10} = mean lives of ^{26}Al and ^{10}Be (year) ($\tau = t_{1/2}/\ln 2$)

This application of cosmogenic isotopic dating has been used to date buried sediments and artifacts in prehistoric sites such as Sterkfontein (Partridge et al., 2003) and Wonderwerk Cave (Matmon et al., 2012) in South Africa.

Bibliography

Bierman, P. R., 1994. Using in situ produced cosmogenic isotopes to estimate rates of landscape evolution: a review from the geomorphic perspective. *Journal of Geophysical Research: Solid Earth (1978–2012)*, **99**(B7), 13885–13896.

Dunai, T. J., 2010. *Cosmogenic Nuclides: Principles, Concepts and Applications in the Earth Surface Sciences*. Cambridge: Cambridge University Press.

Gosse, J. C., and Phillips, F. M., 2001. Terrestrial in situ cosmogenic nuclides: theory and application. *Quaternary Science Reviews*, **20**(14), 1475–1560.

Granger, D. E., 2006. A review of burial dating methods using ^{26}Al and ^{10}Be. In Siame, L., Bourlès, D. L., and Brown, E. T. (eds.), *In Situ-Produced Cosmogenic Nuclides and Quantification of Geological Processes*. Boulder: Geological Society of America. GSA Special Paper 415, pp. 1–16.

Matmon, A., Ron, H., Chazan, M., Porat, N., and Horwitz, L. K., 2012. Reconstructing the history of sediment deposition in caves: a case study from Wonderwerk Cave, South Africa. *Geological Society of America Bulletin*, **124**(3–4), 611–625.

Partridge, T. C., Granger, D. E., Caffee, M. W., and Clarke, R. J., 2003. Lower Pliocene hominid remains from Sterkfontein. *Science*, **300**(5619), 607–612.

D

DATA VISUALIZATION

Erich C. Fisher[1] and Curtis W. Marean[2,3]
[1]School of Human Evolution and Social Change, Arizona State University, Tempe, AZ, USA
[2]Institute of Human Origins, School of Human Evolution and Social Change, Arizona State University, Tempe, AZ, USA
[3]Centre for Coastal Palaeoscience, Nelson Mandela Metropolitan University, Port Elizabeth, Eastern Cape, South Africa

Synonyms

Graphic design; Information graphics (infographics)

Definition

Data visualization. Pictorial representations that are derived from qualitative or quantitative raw data to infer process or patterns in phenomena. Data visualization is closely linked to *informatics*, the collection, indexing, storage, retrieval, analysis, synthesis, and dissemination of data (He, 2003) and *graphic design*, which is the study of the technology, implementation, and social impact on human visual communication (Frascara, 1988).

Introduction

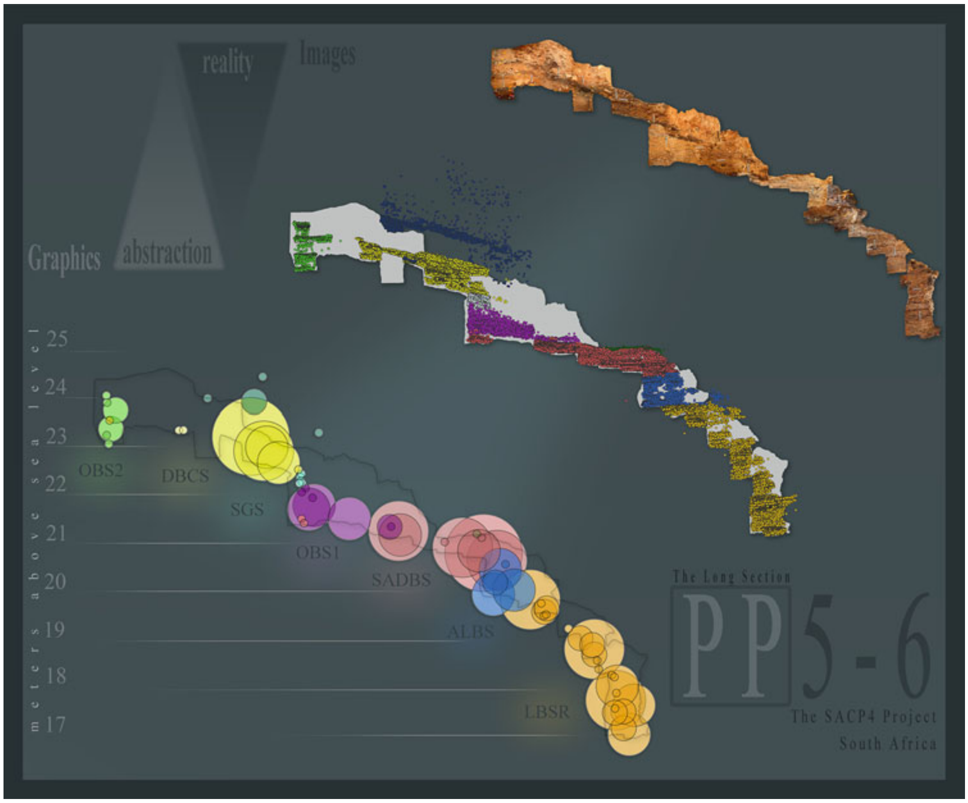
Multimedia learning theory posits that the human brain creates dynamic associations between words, pictures, and auditory information to maximize learning capability (Mayer, 2001). Sociological studies of scientific practices have also showed that visualizations are a key part of the discovery process and the transmission of information among individuals (Lynch and Woolgar, 1990; Dibiase et al., 1992; Suárez, 2010; Allamel-Raffin, 2011; Gelfert, 2011). While words alone are an effective medium to transmit complex information, they may be less effective than when they are paired with pictures. Thus, one needs only to look at the myriad of papers, presentations, or field books to see that visualization is innate to scientific practice regardless of time period, theme, scale, or methods.

Visualizations are versatile tools because they work as a heuristic device capable of distilling real-world experiences and phenomena into simplified abstractions that can convey specific ideas, meanings, or knowledge (Gooding, 2008; Wang and Shen, 2011). The abstraction of visual representations is graded. At one end of the spectrum are *images,* like photographs, which mimic the real world and whose internal elements have no inherent meaning. On the other end of the spectrum are *graphics*, like maps, which are abstracted representations of the real world that are used to convey specific meaning through their symbolic representations. The level of abstraction and inherent meaning between images and graphics thus creates a fundamental difference in how these visualizations are used (MacEachren, 1994): *images* lead one to question the picture itself, whereas *graphics* lead one to question the relationship between what is being symbolized within the picture. These concepts are represented in Figure 1, which shows how a photographic image can be progressively simplified and abstracted to convey only specific information. By abstracting the image, it is much easier to analyze the relationships between the symbols.

Visualizations can also be used to describe empirical observations and to develop hypotheses. As visual *models*, they can also be tested and refined themselves. Thus, everything from informal field sketches (sometimes of dubious quality) to formalized maps, graphs, charts, figures, photographs, and animations all serve the same purpose. They allow the geoarchaeologist to conceptualize complex ideas,

Electronic Supplementary Material The online version of this chapter (doi:10.1007/978-1-4020-4409-0_56) contains supplementary material, which is available to authorized users.

A.S. Gilbert (ed.), *Encyclopedia of Geoarchaeology*, DOI 10.1007/978-1-4020-4409-0,



Data Visualization, Figure 1 Differences between graphics and images. This figure shows the PP5-6 long section at varying levels of abstraction to illustrate the difference between images and graphics. The photomosaic of the long section in the *upper right* corner most closely approaches reality, and interpretation is centered on the image itself. In the center, the image has been abstracted as a silhouette overlaid by points representing archaeological plotted finds color-coded to major stratigraphic groups. The interpretation is now shifted to the relationships between the elements within the graphic and not the long section. In the *lower left*, the graphic is abstracted further to control what information is conveyed to the observer: in this case, the density of plotted finds within sub-stratigraphic groups.

organize when and how to test ideas, develop new ideas, and describe and disseminate results.

This contribution will review how new digital technologies are changing the way data are visualized. Several common applications of data visualization within geoarchaeology and the broader archaeological sciences are presented, with critiques regarding how some visualization methods are used in the process. Effective integration of a wide diversity of disciplines is crucial to archaeological research. Data visualization can assist this, so a brief example is offered to show how multi-proxy datasets derived from artifact plots, micromorphology, stratigraphy, and optically stimulated luminescence (OSL) data are currently being integrated into empirical 3D models with the intention of testing hypotheses about site formation and human occupation at the site of Pinnacle Point 5-6 (PP5-6), near Mossel Bay, South Africa.

Georchaeological visualization in the digital age

Only a few years ago, the production of visualizations was a specialized and typically non-digital affair. Today, the visualization process – from field data collection to final image production – is nearly or entirely digital. This change can be attributed to exponential increases in computing power over the past three decades alongside the concomitant decrease in computer price/performance ratios (Moore, 1975; Dongarra et al., 2010; Fuller and Millett, 2011). Simultaneously, newer software and digital input devices like cameras, scanners, and measurement tools are now more commonly available and affordable.

The plethora of new software has firmly shifted the creation of data visualizations from specialists to the end user. On the one hand, this is beneficial to researchers, who are now empowered to create visualizations that suit their needs. On the other hand, empowering end users who may have little or no specialized training in GIS, cartography, graphics design, or even statistics (to name but a few) emphasizes their commonsense intuitions that may run counter to established expert knowledge. This phenomenon is variably described in cognitive science as *naïve* "geography" (Egenhofer and Mark, 1995), "realism" (Smallman and Cook, 2011), "cartography" (Hegarty et al., 2009), and "statistics" (Trumpower and Fellus, 2008).

One example of data visualization naïvety is that realism increases performance. Yet, Hegarty et al. (2009) found that increasing map realism also increased a person's data extraction time by ~10 %. Another example (which happens also to be common among archaeologists) is that small-scale maps equate to small areas, and vice versa. In fact, the opposite is true (Harris, 2006): small geographic areas have larger representative fractions (e.g., 1:5) than small-scale maps (e.g., 1:250,000) that represent larger areas. Furthermore, there is abundant research on the mechanics, cognition, and psychology underlying our ability to see and understand visualizations, yet this information may be unknown to nonspecialists (Ware, 2013). This includes the numerous optical illusions, biases, and limitations that influence how people subjectively perceive space, depth, color, and movement.

Color, for example, is perceived in context, so that the same color can appear differently based on its surroundings within an image (Ware, 1988). Chromatic aberration and insensitivity of the human eye to short-wavelength light also makes the color blue a poor choice for fine details that might appear fuzzy, especially on black backgrounds (Jackson et al., 1994).

The take-home message is that while we may all be able to create detailed and complex data visualizations, it is still prudent to work within a multidisciplinary framework with specialists in each respective field who may be able to provide expert knowledge to optimize the data visualization task at hand. Otherwise, simple mistakes may lead to significant problems in the way the visualization is seen and understood.

Application of data visualization within geoarchaeology

The use of data visualizations within geoarchaeology and the broader archaeological sciences is also changing as digital technologies become more common. By far the most frequent application of data visualizations has been what we refer to here as *visual aids*, which supplement analyses, discussions, or presentations. Visual aids can be static imagery, graphics, or animations, but they share the underlying commonality of being generalizations derived from particular observations, thus making them inductively based.

Maps are among the commonest examples of visual aids, and multiple studies have shown that the usefulness of maps lies in their generalizing capabilities to develop ideas or hypotheses from complex real-world phenomena (MacEachren and Ganter, 1990; Fisher et al., 1993; MacEachren, 1995; Häberling et al., 2008; Hegarty et al., 2009). Similarly, scientific visualization methods for exploratory and summary data analysis, like diagrams, flow charts, and graphs, are also visual aids. A good example of visual aids in geoarchaeology is Hassan's (1978) well-illustrated discussion on the contributions of sedimentological analysis within archaeology, which included flow charts, a Sankey flow diagram, oblique 3D cross sections, stratigraphic profiles, ternary diagrams, thematic illustrations, and even a stacked, shaded line graph. Visual aids can also be interactive, as shown by Entwistle et al. (2009), who used 3D images to study soil chemical distributions at an archaeological site in the Scottish central highlands. The similarities between visual aids, as a class of data visualization, are thus not within the technical complexity or type of visualization rather than in their application as a multimedia supplement.

Site prospection methods have also been applied largely as visual aids independently of the method being used (e.g., radar or aerial imagery). Here, the focus is on condensing large amounts of data to identify specific features that can then be analyzed in more detail. Wynn's (1986) review of remote sensing methods in archaeology clearly emphasized their data collection capabilities as a way to survey and summarize large areas rapidly. Conyers (2004) also highlighted the exploratory role of ground penetrating radar (GPR) as a rapid and noninvasive method. Dalan (2008) further suggested that archaeogeophysics remained limited to a "confirmatory method." Meanwhile, Gaffney's (2008) updated review on archaeological geophysical techniques similarly emphasized their prospection and 3D modeling capabilities, but he stopped short of articulating how the datasets could be applied empirically. More recently, however, Conyers (2010) and Conyers and Leckebusch (2010) have suggested that the application of GPR is moving from prospection to being a primary and empirical data source.

The widespread application of visual aids has thus proved to be a useful tool for research and data dissemination. But, focusing only on the acquisition and summary of data in a visual manner potentially hobbles scientific progress toward also using data visualization as an empirical tool. Perhaps this is why Llobera (2011, 194) has noted that:

> Archaeological visualization has not developed much since the introduction of stratigraphic sketches by Boucher de Perthes (1847) and distribution maps by O. G. S. Crawford during the early twentieth century. Even with the incorporation of advanced tools such as GIS, the use and production of forms of visual communication remain painfully narrow. . . . For the most part, the role of visual output is restricted to legitimizing our output rather than as an active element within the archaeological reasoning machinery.

3D, VR, and animations

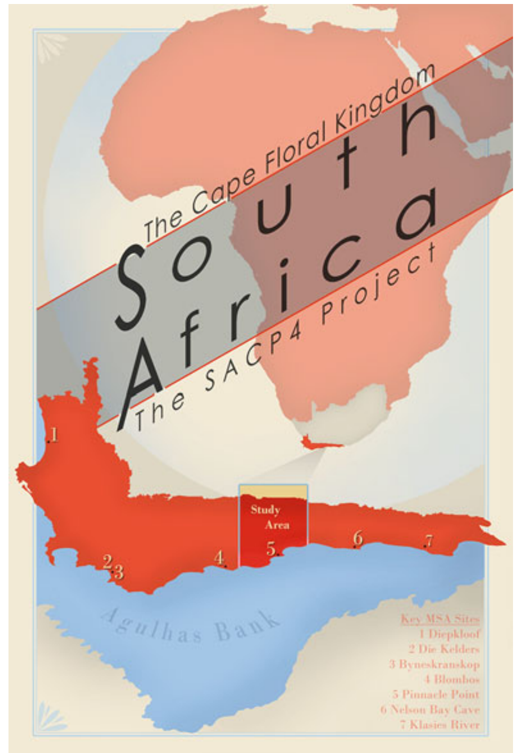
3D and virtual reality (VR) are broadly seen as a superior way to visualize data (Barceló et al., 2000; Gillings, 2005). Multidimensionality provides an immersive and interactive experience that augments learning in users with already high spatial abilities as well as providing a compensatory effect in learners with low spatial abilities (Höffler, 2010). Kumar and Benbasat (2004) even found that 3D graphs outperform 2D graphs overall in data extraction exercises, whereas Wickens et al. (1994) found that 3D representations of surfaces were more easily understood than 2D representations.

3D, VR, and animation appear to be the data analysis and dissemination models of the future, as recognized in the many software packages that now offer native 3D manipulation of data. ESRI ArcGIS, for example, supports multidimensional rendering and analysis of raster and vector datasets via ArcScene and ArcGlobe. GRASS GIS supports volumetric modeling as well as advanced spatial analysis capabilities. The stereo analyst extension for ERDAS Imagine 2011 allows users to extract 3D data from digital stereo models. GPR-SLICE provides detailed 3D (i.e., volumetric) and 2.5D (i.e., non-volumetric depth of field) rendering of ground penetrating radar data. Statistical software packages like SYSTAT, PASW/SPSS, and SAS, as well as add-ins to Microsoft Excel like XLSTAT, allow the user to generate 3D graphs and charts from tabular datasets. Image creation and processing software like Adobe Photoshop and Illustrator CS5 also offer 3D design utilities. The industry standard format for publications, Adobe PDF, also now natively supports 30 different 3D model formats including VRML (for web-based 3D) and KMZ (Google Earth). Lastly, many scientific journals now accept animations and 3D models within PDFs or as supplementary online materials.

Curiously though, most applications of 3D data visualization seem to conform to Llobera's (2011) observation that they are used only to legitimize what we already know, thus being merely *visual aids*. Within the archaeological sciences, this narrow application may be due to the developmental history of 3D and VR, which has been largely unorthodox and haphazard (Gillings, 2000, 2002). Most software is not written for an archaeological audience or its scales of interest. ESRI ArcGIS, for example, is progressively being tailored toward small-scale 3D geographic applications like urban planning (ESRI, 2011). This may aid regional geomorphological studies and archaeological surveys, but it could inhibit large-scale site-based 3D studies. The same can be said of the immensely popular Google Earth, which is also designed for regional applications.

The realism inherent within 3D and VR models may also be a limiting factor in their current application. 3D and VR models are becoming almost too convincing, which, at least, inhibits critical questioning and, at most, can imbue these visualizations with a false sense of authority (Lock, 2003). This, and their esoteric development, has led Gillings (2005) to suggest that 3D and VR models are seen to be self-evident, so they are developed ex post facto without any hypotheses leading to the model development and testing process. The end result is that these showy visualizations are thus often dismissed because they are seen to be "pseudoscientific" (see also McCoy and Ladefoged, 2009).

Conventional use is changing, however. Barceló (2001) argued that VR needs to move away from presentation toward explanation, where the digital environments become testable visual models in their own right. Herries and Fisher (2010) tested 3D models of mineral magnetic data against micromorphological, geochronological, and stratigraphic observations to illustrate complex

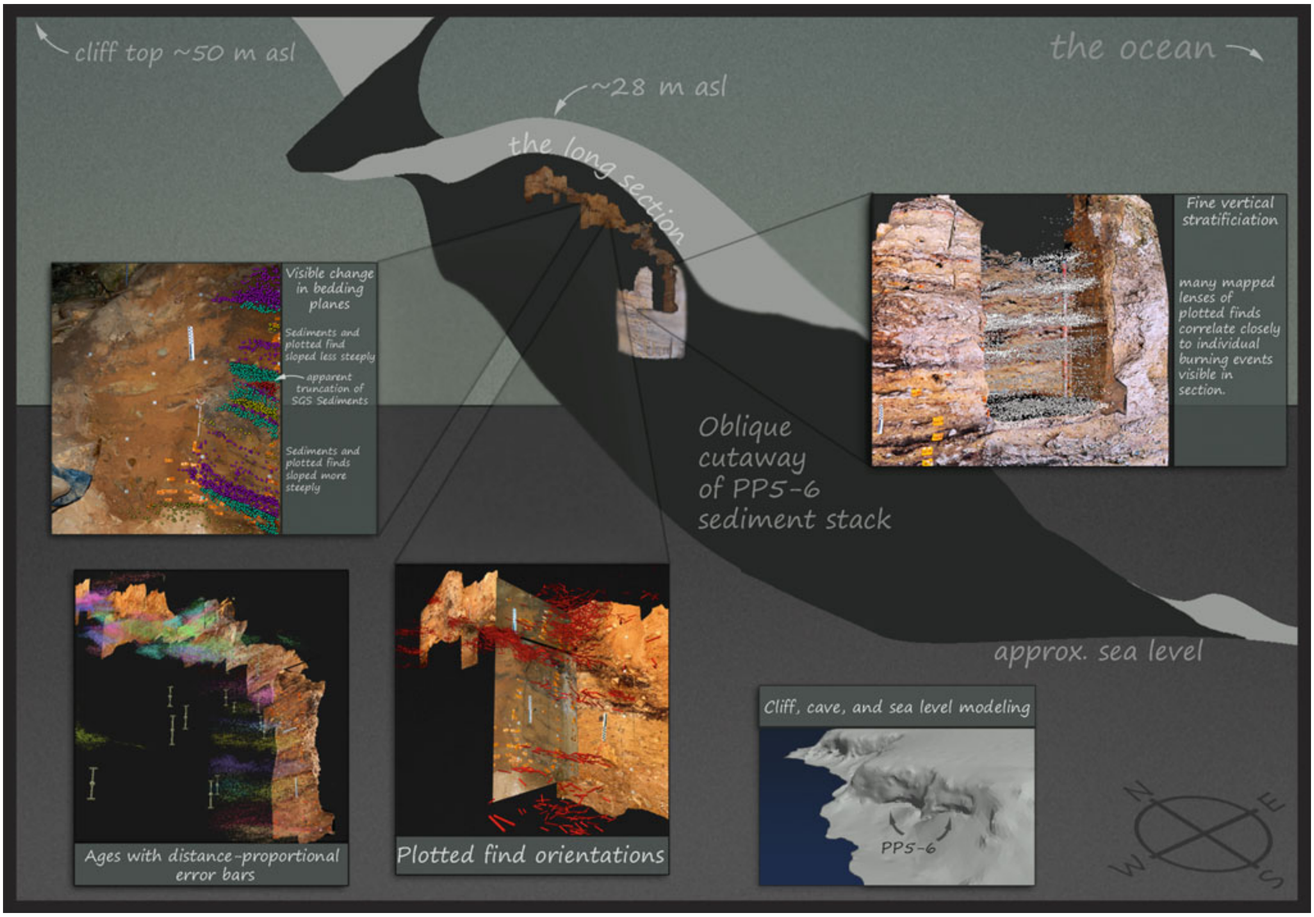


Data Visualization, Figure 2 The SACP4 project study area within the Cape Floral Region of South Africa. Many sea caves on the south coast of South Africa preserve paleoenvironmental, paleoclimatic, and paleoanthropological records from the Middle and Late Pleistocene. SACP4 is studying a series of caves at Pinnacle Point in the heart of the Cape Floral Region.

spatiotemporal patterning in fire use at cave PP13B in South Africa. Fisher et al. (2010) tested 3D spatiotemporal models of coastline changes across the south coast of South Africa using geochronological, strontium isotope, and archaeological datasets. In both examples, the 3D models were used as a primary, independent, and testable dataset that was governed by underlying hypotheses. Furthermore, to communicate more effectively the complex 3D patterning, both papers integrated static imagery and narrated 3D animations. Lastly, Fisher et al. (2010) provided detailed metadata on the methodology, computer scripting, and model parameters that enable the duplication of the results. Drawing upon the theme of building and using empirical 3D GIS models of geoarchaeological data, the following section will present a brief case study focused on site PP5-6 in South Africa.

The PP5-6 3D GIS

Pinnacle Point is located within the Cape Floral Region on the south coast of South Africa. Similar to other sites along the south coast, a series of sea caves at Pinnacle Point preserve long sedimentary records of climate, environment, and human evolution (Marean et al., 2007; Marean, 2010) (Figure 2). Since 2006, researchers from the SACP4



Data Visualization, Figure 3 The SACP4 3D GIS: This image provides an overview of the PP5-6 3D GIS and how multi-proxy datasets have been integrated in the framework to tackle complex archaeological and geoarchaeological questions.

project led by Marean have focused on site PP5-6, a >100 m long cavity that was incised into the cliff face by multiple past high sea stands. Sediments incrementally built up in front of the cavity since the last interglacial high stand (~125,000 years ago), providing the substrate for past human occupations at the site.

Overviews of SACP4 excavation methods can be found in Marean et al. (2007) and Marean et al. (2010). Excavations at PP5-6 have been conducted over a 30 m long distance roughly north-south, spanning over 14 vertical meters. The broad spatial extent has required detailed analysis to understand the complex history of site formation. These ongoing studies have included geochronology, micromorphology, magnetic susceptibility, on-site macrostratigraphic characterizations, and mapping.

All excavation coordinate data and imagery are integrated into a 3D GIS model using ESRI ArcGIS 10. Nearly 250,000 total station plotted finds have been mapped to date. These plotted finds represent, among other things, archaeological stone, ochre, or ostrich eggshell artifacts, as well as faunal remains (mollusks, mammals, etc.). Section imagery was captured using Nikon digital SLR cameras under consistent camera orientation, lighting, focal length, aperture, and sediment moisture conditions. All images were post-processed for geometric distortion in Adobe Photoshop CS5 using unique camera model/lens correction profiles. Photographic mosaics were created using PTGui v.9 and Adobe Photoshop before being geo-rectified using ArcGIS. Additional details on integrating the photography into ArcScene will be made available in forthcoming publications.

Integrating the plotted finds and the geometrically rectified section photography in 3D allows unprecedented recognition of vertical and lateral patterning in the plotted finds. The resolution of the 3D plotted finds is so fine that empirical observations of features like changes in bedding planes can be identified independently from other data sources or methods where they would be otherwise invisible (Figure 3). Many small lenses of plotted finds also correlate closely with discrete burning events seen in the sections, which represent individual hearths that were likely

Data Visualization, Video 1 The PP5-6 3D GIS supplementary video was produced using a combination of software. ArcGIS 10 ArcScene and ArcGlobe were used to develop the 3D GIS and subsequent animation sequences. Adobe Photoshop CS5 was used to create other still graphics. Audio files were recorded using a Samson S11 cardioid microphone and Olympus WS-210S digital recorder. Audacity 1.3 was used to remove background noise, sound normalization and compression, and equalization using the EMI 78 standard. The video was produced using Corel VideoStudio Pro ×4. The aspect ratio was set to 16:9 widescreen format. The final movie was exported using the H.264 codec.

used for only a limited time. Plotted find orientation is also recorded, and it can be used to test for postdepositional disturbances (Bernatchez, 2010) and to create directional flow models to study erosional patterns at the site.

The 3D plotted find point data was analyzed and grouped based on the structure (e.g., laminations, clusters, absences, etc.) visible within the dataset. To minimize preexisting bias, these points were analyzed using a single point color. Thereafter, the groupings were tested against infield stratigraphic observations, thereby allowing simultaneous testing of field assignments and the 3D analysis. The final stratigraphic groupings are represented in Figure 1. When micromorphology and OSL age estimates are also integrated into the 3D GIS, a third invaluable and independent test of the stratigraphic models is created.

The result is a comprehensive characterization of the PP5-6 stratigraphy derived from multiple, independent datasets (Figure 3). The PP5-6 3D GIS has thus proved to be a valuable *visual aid* and *empirical* model. As a visual aid, it provides unprecedented access into the archaeological deposits, allowing researchers to see and check the accuracy of new data and spot new and interesting features for future study. The 3D framework is also an invaluable tool to show and explain complex ideas using animations and still imagery within and outside the main research group. To showcase the animated capabilities of the PP5-6 3D GIS, and similar kinds of datasets, a brief supplementary movie is provided with this entry (Video 1). But when used as a deductive reasoning tool, the PP5-6 3D GIS also allows SACP4 researchers to test observations and hypotheses relating to the archaeological and sedimentological records. 3D visualization may not be necessary to address each research question, but on the whole it provides an immersive, dynamic, and multi-local experience that is lacking in 2D imagery. Contrary to Llobera's perspective (2011), the state of data visualization within geoarchaeological and the broader archaeological sciences is actually quite positive. Newer software, faster computers, and flexible solutions to tackle complex problems will ultimately provide innovative and better ways to visually observe and test scientific data.

Bibliography

Allamel-Raffin, C., 2011. The meaning of a scientific image: case study in nanoscience a semiotic approach. *NanoEthics*, **5**(2), 165–173.

Barceló, J. A., 2001. Virtual reality and scientific visualization: working with models and hypotheses. *International Journal of Modern Physics C*, **12**(4), 569–580.

Barceló, J. A., Forte, M., and Sanders, D. H., 2000. *Virtual Reality in Archaeology*. Oxford: Archaeopress. British Archaeological Reports, International Series, Vol. 843.

Bernatchez, J. A., 2010. Taphonomic implications of orientation of plotted finds from Pinnacle Point 13B (Mossel Bay, Western Cape Province, South Africa). *Journal of Human Evolution*, **59** (3–4), 274–288.

Boucher de Perthes, J., 1847. *Antiquités celtiques et antédiluviennes. Mémoire sur l'industrie primitive et les arts à leur origine*. Paris, 3 Vols: Treuttel et Wurtz.

Conyers, L. B., 2004. *Ground-Penetrating Radar for Archaeology*, old edn. Walnut Creek, CA: AltaMira.

Conyers, L. B., 2010. Ground-penetrating radar for anthropological research. *Antiquity*, **84**(323), 175–184.

Conyers, L. B., and Leckebusch, J., 2010. Geophysical archaeology research agendas for the future: some ground-penetrating radar examples. *Archaeological Prospection*, **17**(2), 117–123.

Dalan, R. A., 2008. A review of the role of magnetic susceptibility in archaeogeophysical studies in the USA: recent developments and prospects. *Archaeological Prospection*, **15**(1), 1–31.

Dibiase, D., MacEachren, A. M., Krygier, J. B., and Reeves, C., 1992. Animation and the role of map design in scientific visualization. *Cartography and Geographic Information Systems*, **19**(4), 201–214. 265–266.

Dongarra, J. J., Meuer, H. W., Simon, H. D., and Strohmaier, E., 2010. Recent trends in high performance computing. In Bultheel, A., and Cools, R. (eds.), *The Birth of Numerical Analysis*. Singapore/Hackensack, NJ: World Scientific Publishing, pp. 93–107.

Egenhofer, M. J., and Mark, D. M., 1995. Naive geography. In Frank, A. U., and Kuhn, W. (eds.), *Spatial Information Theory: A Theoretical Basis for GIS*. Berlin: Springer. Lecture Notes in Computer Sciences, Vol. 988, pp. 1–15.

Entwistle, J. A., McCaffrey, K. J. W., and Abrahams, P. W., 2009. Three-dimensional (3D) visualisation: the application of terrestrial laser scanning in the investigation of historical Scottish farming townships. *Journal of Archaeological Science*, **36**(3), 860–866.

ESRI, 2011. ArcGIS 10.1 Common Questions: Lidar and 3D.

Fisher, P., Dykes, J., and Wood, J., 1993. Map design and visualization. *Cartographic Journal*, **30**(2), 136–142.

Fisher, E. C., Bar-Matthews, M., Jerardino, A., and Marean, C. W., 2010. Middle and Late Pleistocene paleoscape modeling along the southern coast of South Africa. *Quaternary Science Reviews*, **29**(11–12), 1382–1398.

Frascara, J., 1988. Graphic design: fine art or social science? *Design Issues*, **5**(1), 18–29.

Fuller, S. H., and Millett, L. I., 2011. Computing performance: game over or next level? *Computer*, **44**(1), 31–38.

Gaffney, C., 2008. Detecting trends in the prediction of the buried past: a review of geophysical techniques in archaeology. *Archaeometry*, **50**(2), 313–336.

Gelfert, A., 2011. Model-based representation in scientific practice: new perspectives. *Studies in History and Philosophy of Science Part A*, **42**(2), 251–252.

Gillings, M., 2000. Plans, elevations and virtual worlds: the development of techniques for the routine construction of hyperreal simulations. In Barceló, J. A., Forte, M., and Sanders, D. H. (eds.), *Virtual Reality in Archaeology*. Oxford: Archaeopress. British Archaeological Reports, International Series, Vol. 843, pp. 59–70.

Gillings, M., 2002. Virtual archaeologies and the hyper-real: or, what does it mean to describe something as virtually-real? In Fisher, P. F., and Unwin, D. (eds.), *Virtual Reality in Geography*. London: Taylor and Francis, pp. 17–34.

Gillings, M., 2005. The real, the virtually real, and the hyperreal: the role of VR in archaeology. In Smiles, S., and Moser, S. (eds.), *Envisioning the Past: Archaeology and the Image*. Oxford: Blackwell, pp. 223–239.

Gooding, D. C., 2008. Envisioning explanations: the art in science. In Frischer, B., and Dakouri-Hild, A. (eds.), *Beyond Illustration: 2D and 3D Digital Technologies as Tools for Discovery in Archaeology*. Oxford: Archaeopress. British Archaeological Reports, International Series, Vol. 1805, pp. 1–19.

Häberling, C., Bär, H., and Hurni, L., 2008. Proposed cartographic design principles for 3D maps: a contribution to an extended cartographic theory. *Cartographica: The International Journal for Geographic Information and Geovisualization*, **43**(3), 175–188.

Harris, T. M., 2006. Scale as artifact: GIS, ecological fallacy, and archaeological analysis. In Lock, G. R., and Molyneaux, B. (eds.), *Confronting Scale in Archaeology: Issues of Theory and Practice*. New York: Springer, pp. 39–53.

Hassan, F. A., 1978. Sediments in archaeology: methods and implications for palaeoenvironmental and cultural analysis. *Journal of Field Archaeology*, **5**(2), 197–213.

He, S., 2003. Informatics: a brief survey. *Electronic Library*, **21**(2), 117–122.

Hegarty, M., Smallman, H. S., Stull, A. T., and Canham, M. S., 2009. Naïve cartography: how intuitions about display configuration can hurt performance. *Cartographica: The International Journal for Geographic Information and Geovisualization*, **44**(3), 171–186.

Herries, A. I. R., and Fisher, E. C., 2010. Multidimensional GIS modeling of magnetic mineralogy as a proxy for fire use and spatial patterning: evidence from the Middle Stone Age bearing sea cave of Pinnacle Point 13B (Western Cape, South Africa). *Journal of Human Evolution*, **59**(3–4), 306–320.

Höffler, T. N., 2010. Spatial ability: its influence on learning with visualizations – a meta-analytic review. *Educational Psychology Review*, **22**(3), 245–269.

Jackson, R., MacDonald, L. W., and Freeman, K., 1994. *Computer Generated Colour: A Practical Guide to Presentation and Display*. Chichester/New York: Wiley.

Kumar, N., and Benbasat, I., 2004. The effect of relationship encoding, task type, and complexity on information representation: an empirical evaluation of 2D and 3D line graphs. *MIS Quarterly*, **28**(2), 255–281.

Llobera, M., 2011. Archaeological visualization: towards an archaeological information science (AISc). *Journal of Archaeological Method and Theory*, **18**(3), 193–223.

Lock, G. R., 2003. *Using Computers in Archaeology: Towards Virtual Pasts*. London/New York: Routledge.

Lynch, M., and Woolgar, S., 1990. *Representation in Scientific Practice*. Cambridge: MIT Press.

MacEachren, A. M., 1994. *Some Truth with Maps: A Primer on Symbolization and Design*. Washington, DC: Association of American Geographers.

MacEachren, A. M., 1995. *How Maps Work: Representation, Visualization, and Design*. New York: Guilford Press.

MacEachren, A. M., and Ganter, J. H., 1990. A pattern identification approach to cartographic visualization. *Cartographica: The International Journal for Geographic Information and Geovisualization*, **27**(2), 64–81.

Marean, C. W., 2010. Pinnacle Point Cave 13B (Western Cape Province, South Africa) in context: the Cape Floral kingdom, shellfish, and modern human origins. *Journal of Human Evolution*, **59**(3–4), 425–443.

Marean, C. W., Bar-Matthews, M., Bernatchez, J., Fisher, E., Goldberg, P., Herries, A. I. R., Jacobs, Z., Jerardino, A., Karkanas, P., Minichillo, T., Nilssen, P. J., Thompson, E., Watts, I., and Williams, H. M., 2007. Early human use of marine resources and pigment in South Africa during the Middle Pleistocene. *Nature*, **449**(7164), 905–908.

Marean, C. W., Bar-Mathews, M., Fisher, E. C., Goldberg, P., Herries, A., Karkanas, P., Nilssen, P. J., and Thompson, E., 2010. The stratigraphy of the Middle Stone Age sediments at Pinnacle Point Cave 13B (Mossel Bay, Western Cape Province, South Africa). *Journal of Human Evolution*, **59**(3–4), 234–255.

Mayer, R. E., 2001. *Multimedia Learning*. Cambridge/New York: Cambridge University Press.

McCoy, M. D., and Ladefoged, T. N., 2009. New developments in the use of spatial technology in archaeology. *Journal of Archaeological Research*, **17**(3), 263–295.

Moore, G. E., 1975. Progress in digital integrated electronics. *Electron Devices Meeting, 1975 International*, **21**, 11–13.

Smallman, H. S., and Cook, M. B., 2011. Naïve realism: folk fallacies in the design and use of visual displays. *Topics in Cognitive Science*, **3**(3), 579–608.

Suárez, M., 2010. Scientific representation. *Philosophy Compass*, **5**(1), 91–101.

Trumpower, D. L., and Fellus, O., 2008. Naïve statistics: intuitive analysis of variance. In: Love, B. C., McRae, K., and Sloutsky, V. M. (eds.), *Proceedings of the 30th Annual Conference of the*

Cognitive Science Society. Austin, TX: Cognitive Science Society, pp. 499–503.
Wang, C.-L., and Shen, H.-W., 2011. Information theory in scientific visualization. *Entropy*, **13**(1), 254–273.
Ware, C., 1988. Color sequences for univariate maps: theory, experiments and principles. *Computer Graphics and Applications IEEE*, **8**(5), 41–49.
Ware, C., 2013. *Information Visualization: Perception for Design*, 3rd edn. Waltham, MA/Amsterdam: Morgan Kaufman/Elsevier.
Wickens, C. D., Merwin, D. H., and Lin, E. L., 1994. Implications of graphics enhancements for the visualization of scientific data: dimensional integrality, stereopsis, motion, and mesh. *Human Factors*, **36**(1), 44–61.
Wynn, J. C., 1986. A review of geophysical methods used in archaeology. *Geoarchaeology*, **1**(3), 245–257.

Cross-references

Pinnacle Point

DENDROCHRONOLOGY

Jonathan G. A. Lageard
Division of Geography and Environmental Management, School of Science and the Environment, Faculty of Science and Engineering, Manchester Metropolitan University, Manchester, UK

Synonyms

Tree-ring dating

Definition

The word dendrochronology comprises three parts, originating from Greek "dendron" (tree), "chronos" (time), and -ology (study of), and is defined as "the science of dating tree rings" (Kaennel and Schweingruber, 1995, 65). It is a chronometric ("absolute") dating technique that employs records of annual growth increments in trees to establish the calendar age of wood samples taken from living or nonliving trees and from wood that has been used by humans.

History

Interest in tree growth and the rings produced by this phenomenon has its origin in fifteenth century AD and possibly before. Leonardo da Vinci is often cited as the first notable scientist not only to write about tree growth but also to speculate that tree rings and environmental parameters (rainfall) in the growing season might be linked (Schweingruber, 1988; Speer, 2010). In the seventeenth century, the invention of the microscope paved the way for wood anatomical studies, and by the mid-eighteenth century, an understanding of tree-ring development had emerged from the work of Theodor Hartig and others (Schweingruber, 1988). It was not until the early twentieth century that the principle of cross dating was fully established and consistently applied by Andrew Ellicott Douglass (1867–1962), who is universally acknowledged as the "father of dendrochronology" (Schweingruber, 1988, 257). Douglass and a team of co-workers applied the newly emerging technique of dendrochronology to date archaeological sites in the American Southwest. In 1923, the National Geographic Society sponsored a "Beam Expedition" (Nash, 1999), which led to the sampling of numerous timbers and the establishment of the first long tree-ring chronology back to AD 1280, as well as a 585-year floating chronology (not tied to the ring sequence ending in modern time) (Schweingruber, 1988). Douglass founded the first laboratory dedicated to dendrochronological research in 1937, the Laboratory of Tree-Ring Research (Tuscon, Arizona), which has remained a center of excellence in teaching and research and has contributed significantly, although not in isolation, to the current large global network of tree-ring laboratories (Grissino-Mayer, 2014).

Since the early twentieth century, dendrochronologists have produced records of chronometrically dated tree-ring patterns, i.e., tree-ring chronologies, stretching further and further back in time. In North America, two key species in this chronology development have been the giant sequoia (*Sequoiadendron giganteum*) and bristlecone pine (*Pinus longaeva*). The latter is particularly useful in dendrochronology, being very long lived, as its Latin name suggests, with some individual trees living in excess of 5,000 years (Rocky Mountain Tree-Ring Research, 2013) and a continuous master chronology extending back 8,681 years put in place by the early 1980s (Ferguson and Graybill, 1983). Their high-altitude habitat, in areas such as the White Mountains in California, makes bristlecone pines sensitive to temperature and precipitation. As a result, this species has been important in the development of long-term climate reconstructions (Scuderi, 1993; Woodhouse et al., 2011), in determining the global effects of volcanic eruptions on ecosystems (LaMarche and Hirschboeck, 1984), and in calibrating the radiocarbon timescale (Walker, 2005, 32–33).

In western Europe, the key species for dendrochronology are both oaks (*Quercus patrea* and *Q. robur*) due to their consistent growth patterns that rarely exhibit missing or false rings and their widespread occurrence both in natural environments and those associated with human activity, e.g., building timbers. Work began on producing long oak chronologies in the 1960s and 1970s, mainly in Germany and Ireland, but it was not until the early 1980s that the first long European oak chronologies were finalized (Pilcher et al., 1984; Baillie, 1995). A large network of local and regional chronologies has now been developed, providing the basis for routine dating of archaeological timbers (Haneca et al., 2009), as well as applications in climate and other reconstructions (Rinne et al., 2013). Oak is a much shorter-lived species than bristlecone pine, and most specimens rarely exceed an age of 200 years. Therefore, chronology building in western Europe has been based on cross dating of many samples from living trees, buildings, and trunks preserved within peat bogs.

Tree-ring chronologies now stretch back into the last ice age based on trees that grew in areas less influenced by the immediate effects of ice advances. German oak chronologies now cover the Holocene (Becker, 1993), and they have been extended back into the last glacial period using a floating Preboreal Pine Chronology of previously unknown age (Friedrich et al., 1998, 1999). This dating is based on dendrochronological cross matching (see "Cross-dating and chronology building") and on radiocarbon wiggle matching (Baillie, 1995, 69–72). Although chronometric dating cannot at present be guaranteed, sites from southern and central Europe have produced tree-ring records that date to around 14,300 years BP (Kaiser et al., 2012). A BP date indicates years "before present," where the present is set at AD 1950 as the baseline standard for radiocarbon dating. Future sampling in these geographical areas and the extension of chronologies may well lead to a chronometric late-glacial growth record with significant implications for advancements in radiocarbon calibration and for improved understanding of past climate change.

In the southern hemisphere, there are also significant subfossil (the preserved remains of a living organism that has undergone limited physical and chemical change) tree-ring records forming floating chronologies potentially as far back as 45,000–25,000 years BP (Turney et al., 2010). These have been created following the sampling of subfossil Kauri (*Agathis australis*) buried in bogs in New Zealand. This long-lived species produces annual tree rings that reveal a marked sensitivity to climate (Hogg et al., 2012). Turney et al. (2010) highlight the possibility that further "harvesting" of these trees and associated sampling for dendrochronology could have significant implications for radiocarbon calibration (see "Pollution: air and soil (dendrochemistry)"), possibly as far back as 60,000 BP.

Long tree-ring chronologies have now been constructed for many areas across the globe, with their extent limited only by the availability of wood of appropriate age. Dendrochronology has developed in midlatitude areas, where tree growth is governed by seasonal weather patterns that produce distinct annual growth increments. Lack of distinct seasonality in the tropics initially made dendrochronology challenging (Worbes, 2002), but ring width and isotopic measurements have isolated annual growth responses permitting the identification of annual signals in wood and assessments of species suitability for dendrochronology and chronology building. Tropical dendrochronology is now an important emerging area within the subject (cf. Robertson et al., 2004; Wils et al., 2011; De Ridder et al., 2013).

Two major traditions emerged in dendrochronology during the twentieth century that have been key to its growth: the North American tradition with notable academics who continued the work of Douglass, including Schulman, Smiley, Hawley, Giddings, Haury, and Fritts; and the European tradition, led among others by Huber, Liese, Becker, Eckstein, Schweingruber, and Baillie.

Dendrochronology, Table 1 Examples of current dendrochronology-specific conferences, meetings, workshops, courses, and resources

Type	Name/details
International conferences	International Conference on Dendrochronology/ICD or World Dendro (9th held in Melbourne, Australia, 13–17 January, 2014) EuroDendro AmeriDendro/The Association of American Geographers (AAG) Asian Dendrochronology Association (ADA)
Specialist meetings	Tree Rings in Archaeology, Climatology and Ecology (TRACE)
Dendroecological fieldweeks	North America, Europe, Asia
Specialist courses/ workshops	Laboratory of Tree-Ring Research Summer School (USA) Wood Anatomy and Tree-Ring Ecology (Switzerland) International Workshop of Tropical Dendrochronology (Brazil)
Databases	International Tree-Ring Data Bank (ITRDB) The Bibliography of Dendrochronology (see Grissino-Mayer 2014)
Journals	*Tree-Ring Research*, formerly *Tree-Ring Bulletin* (North American) *Dendrochronologia* (European)

Dendrochronologists now comprise a global community brought together by similar research interests, international training, research collaborations, and conferences. Tree-ring analyses have a wide range of applications (see below) that are reflected in the vast array of journals in which dendrochronological research is now published, although the subject's roots and traditions are still clearly evident in the two main tree-ring specific journals and in the regular regional meetings held in both North America and Europe (Table 1). Tree-ring research is now well established or becoming established in other areas, notably South America, Africa, and throughout Asia, as exemplified by the growth of new organizations such as the Asian Dendrochronology Association (ADA). For extended coverage of the history of dendrochronology, see Schweingruber (1988, 255–261), Baillie (1995), Nash (1999), and Speer (2010, 28–42).

Field sampling

Samples for dendrochronological analysis can emanate from a number of sources, including timbers that form part of standing buildings, wood from archaeological sites, trees preserved in peat bogs or other natural environments, and from living trees. A general rule at the outset of all tree-ring projects is to ensure that written permission is

Dendrochronology, Figure 1 Sampling a roof timber (rafter) using a power increment borer, Salisbury Cathedral, UK (Image: J. Lageard).

gained for sample retrieval from appropriate land or property owners.

Standing buildings

Dendrochronology has dealt primarily with dating wood from standing buildings. Some of these may be private homes or public buildings, but many can be under renovation or in varying states of disrepair. It is therefore imperative that insurance is sought, safe access is carefully considered, and all relevant health and safety procedures are followed at all times (English Heritage, 1998). Initially, a trained dendrochronologist should make a building assessment to judge suitability for tree-ring dating. This should include establishing the number of building phases present, type of wood used, presence of sapwood and bark, whether there are sufficient rings, and whether there is evidence of seasoning or timber reuse (English Heritage, 1998).

Samples (ca. 50–150 mm thick) can be taken using a hand or chain saw, but when such access is unavailable, timbers are cored in situ using a powered coring device. This consists of a hollow metal tube sharpened at one end (with saw teeth) which is attached to an electric drill (see Figure 1). Core removal is a skilled operation that aims to extract a cylinder of wood parallel to the medullary rays of the timber, ensuring tree rings are sampled at right angles to their original growth positions, with a goal to sample the maximum number of rings. Training is highly recommended from an experienced dendrochronologist to avoid unnecessary damage to buildings and to avoid problems such as core overheating.

Archaeological and natural environment sites

In archaeological and natural environment sites, sampling wood for tree-ring analysis should follow the good practice outlined for standing buildings, but there are other important considerations.

Field locations should be carefully recorded and can also be contextualized within geomorphological maps. Disc samples from trunk sections should be cut at right angles to the bark, ensuring later ring measurements are not distorted. Research focusing on subfossil wood can involve techniques other than dendrochronology, and it is therefore prudent to consider the collection of samples other than wood concurrently, for example, adjacent peat or other sedimentary deposits for the purpose of pollen analysis (cf. Lageard and Ryan, 2013).

Archaeological sites frequently contain only small quantities of wood, often unsuitable for tree-ring dating (e.g., Timberlake and Prag, 2005). At some sites, however, impeded drainage can lead to the preservation of large quantities of timber. Preparation of land for new housing at Kingsley Fields (Cheshire, UK) led to the discovery of a significant Roman industrial site that had engaged in salt production. A total of 355 oak structural timbers were recovered and recorded, including those comprising a substantial wood-lined brine tank. In commercial archaeology, it is rarely possible to date large wood assemblages in their entirety, and a spot dating approach is recommended whereby a small sample is analyzed to better assess dating potential (English Heritage, 1998). At Kingsley Fields, seven samples were initially analyzed in 2002 and a further 34 in 2004 in the post-excavation phase of the project (Tyers, 2012), providing an excellent basis for dating. A large quantity of timbers and their subsamples raises important questions in terms of storage, conservation, and later display, especially with limited local museum space and resources.

Living trees

Deciding which trees to core depends on the nature of the research project. As a rule, dendrochronologists seek trees that demonstrate sensitive growth responses, as these contain more climatic information and are more likely to cross-date (see "Cross-dating and chronology building"). Conversely, complacent growth (low variability among consecutive tree-ring parameters) should be avoided where possible.

The choice of sampling sites can be guided by this distinction, as trees located centrally within the geographical range of a species are more likely to produce complacent ring series, while trees growing in more marginal conditions at altitudinal or latitudinal limits generally exhibit sensitive growth responses (see "Climate reconstruction (dendroclimatology)"). Trees with sensitive ring series can also be found where other limiting factors are present, for instance, pollution, geomorphological processes, and flooding (see "Pollution: air and soil (dendrochemistry)," "Climate reconstruction (dendroclimatology)," and "Impact of water (dendrohydrology)").

Particularly where specific phenomena such as flooding or pollution are being studied, it is important to establish a secondary field site (control site) where trees of the same species are not being influenced by the variable under investigation. The use of control sites is exemplified by Pelfini et al. (2007) in a study of ice movement reflected in larch (*Larix decidua*) growing in debris on top of a small glacier in the western Italian Alps and also in a study of water-table fluctuations caused by solution mining in Cheshire, UK (Lageard and Drew, 2008).

Once a field site has been selected, it is important to collect a representative sample of the trees present. A number of different approaches can be employed; two of the most widely used techniques are (1) defining a specific sampling area and (2) sampling along a transect. The former is often utilized when investigating stand dynamics and the latter in studies involving ecological gradients of elevation, moisture, temperature, or pollution (Watmough, 1999; Lageard et al., 2008).

The approach to coring an individual tree depends largely on the nature of the research project. For example, if the tree is growing on a slope, the force of gravity and the weight of the tree mean the trunk will start to lean downslope. As long as the tree remains securely rooted, it will compensate for this downslope force by bending the base of the trunk with the growth of reaction wood to allow the upper part of the trunk to grow vertically (saber or geotropic growth). In conifers, such compensation causes the formation of a type of reaction wood called compression wood (larger rings with thicker individual cell walls) on the downslope side of the tree, since this side of the trunk is being compressed by the downslope pull of gravity. Compression wood therefore braces the trunk against further bending, enabling it to grow upward. Hardwood trees compensate differently, and the larger rings of reaction wood in this case are called tension wood, which develops on the upslope side to counter and reinforce the stretching caused by gravity pulling in the opposite direction. So if the research aims to date the year in which a slope became unstable, then trees should be sampled from either an upslope or a downslope direction. If, however, the research is trying to understand tree response to meteorological variables, coring parallel to the contour is advisable.

Powered corers can be used, but these are cumbersome, intrusive, and potentially dangerous (Speer, 2010, 77–78), so it is more common to employ a manual Pressler-type increment borer (lengths 100–1,000 mm; diameters normally 5 or 12 mm) to retrieve a cylindrical core from the tree (see Figure 2). If properly maintained, borers may take several hundred cores during their lifetime.

When coring, careful consideration should be given to a range of issues, including sampling height (Brown, 2007), avoiding branches or injuries, aiming for the pith, the number of cores per tree, the number of cores per sample site (Speer, 2010, 176), engaging the borer, and knowing when to stop coring to avoid borer loss. For more extensive advice on borer usage and increment core retrieval, see Grissino-Mayer (2003), Speer (2010, 77–87), and Haglöf (2014). There is little research that investigates tree mortality resulting from increment boring, although Wunder et al. (2011) support general impressions of minimal impacts.

Dendrochronology, Figure 2 Extracting a 5 mm core from a cedar tree (*Cedrus libani*) in Morocco using a manual increment borer (Image: J. Lageard).

Waterlogged wood

Waterlogged wood can provide key dating control at archaeological sites, but mishandling can lead to sample deterioration and loss. As a consequence, guidelines (English Heritage, 2010) have been made available to assist archaeologists. Waterlogged wood is often by its nature very fragile, so great care should be exercised to prevent damage to samples. In particular, attention should be given to the preservation of sapwood and/or bark if present, as these can be crucial in producing precise felling or mortality dates. Increment cores and V-shaped wedges can also be taken where wood is being conserved as part of archaeological investigations (cf. Bridge, 2011), but coring is problematic when weaker sapwood is present (English Heritage, 2010). In many cases, samples can be sawn by hand, but larger timbers may require the use of a chainsaw. Ideally, an experienced dendrochronologist or wood technologist would be involved in collecting samples as part of archaeological investigations and to advise on the suitability of samples for tree-ring dating (English Heritage, 2010).

Laboratory preparation

Increment cores should be processed ideally at the end of each field day. If left too long in enclosed spaces, cores can become moldy, causing problems particularly if dendrochemistry is being investigated. Processing can involve sticking cores with wood glue into grooved wooden channels, ensuring that the rings are correctly oriented according to their growth positions within the tree. Alternatively, in dendrochemical studies, cores can be held in place on the wooden channels using string or elastic bands.

Increment cores and robust samples can be left to air dry. Once dry, samples are sanded in order to differentiate wood structure clearly, particularly ring boundaries, to facilitate subsequent ring-width measurements. Because saw dust is carcinogenic, sanding should occur in well-ventilated facilities, where dust extraction systems are in operation. Powered sanders, with vibrating plates or rotating belts, are best employed using progressively finer sandpaper (Speer, 2010, 92–95).

Waterlogged archaeological samples can be soaked in, or sprayed with, PEG (polyethylene glycol) in order to preserve the integrity of the wood structure, as demonstrated in the conservation of the Tudor battleship Mary Rose and as a precursor to freeze-drying smaller samples before measurement (Babiński, 2011). Wet wood samples are sometimes prepared using a scalpel or a sharp blade in order to differentiate the wood structure clearly (Nayling and Susperregi, 2014).

Measurement

Once wood samples have been collected and prepared, patterns of tree-ring widths or tree-ring series are measured. This process normally deals with rings starting from the oldest, ideally from the center of the tree or pith, and finishing with the most recently formed, located immediately underneath the bark of living trees.

Records of ring-width patterns can be made using the skeleton plot method traditionally employed in North America (Schweingruber, 1988, 47–50; Cook and Kairiukstis, 1990, 43–44; Speer, 2010, 96–100). This technique is still widely employed today and is particularly useful as a training tool (Sheppard, 2014), but ring-width measurements are now more frequently made using computer-based systems capable of an accuracy of 0.01 mm that employ specialized software, measuring stages, and binocular microscopes (Tyers, 1999; Speer, 2010, 102–103). Standard practice is to make consecutive ring-width measurements along at least two radii per sample. Once verified by cross matching, these are combined to make a sample mean.

Other measurement systems use high-resolution flatbed scanners to produce digital images, which can then be manipulated using specialist software such as WinDENDRO (Regent Instruments Inc., 2014) to produce ring-width measurements or to assess other parameters such as blue light reflectance (McCarroll et al., 2002).

Where subsampling of wood and preparation by sanding is impossible, such as for a valuable musical instrument, more sophisticated measuring techniques have been developed based on techniques such as computer tomography (CT). Bill et al. (2012) tested scanners used for medical and industrial purposes on air-dried archaeological oak samples and found that CT scanning was as effective in dating archaeological objects as using conventional techniques, although more time consuming. Bernabei et al. (2010) successfully employed a "Video Time Table," a portable measuring device and high-resolution video camera (VIAS, 2005), to assist in the dating of stringed instruments from the Cherubini Conservatory Collection in Florence, Italy. This system also has the advantages of being noninvasive and deployable on site with minimal disturbance to museums or curators. Similar success was reported by Okochi et al. (2007), who clearly demonstrated that an X-ray CT method could be used for the nondestructive measurement of ring widths from wooden artifacts made of ring-porous Japanese oak (*Quercus mongolica*) and diffuse-porous Japanese beech (*Fagus crenata*).

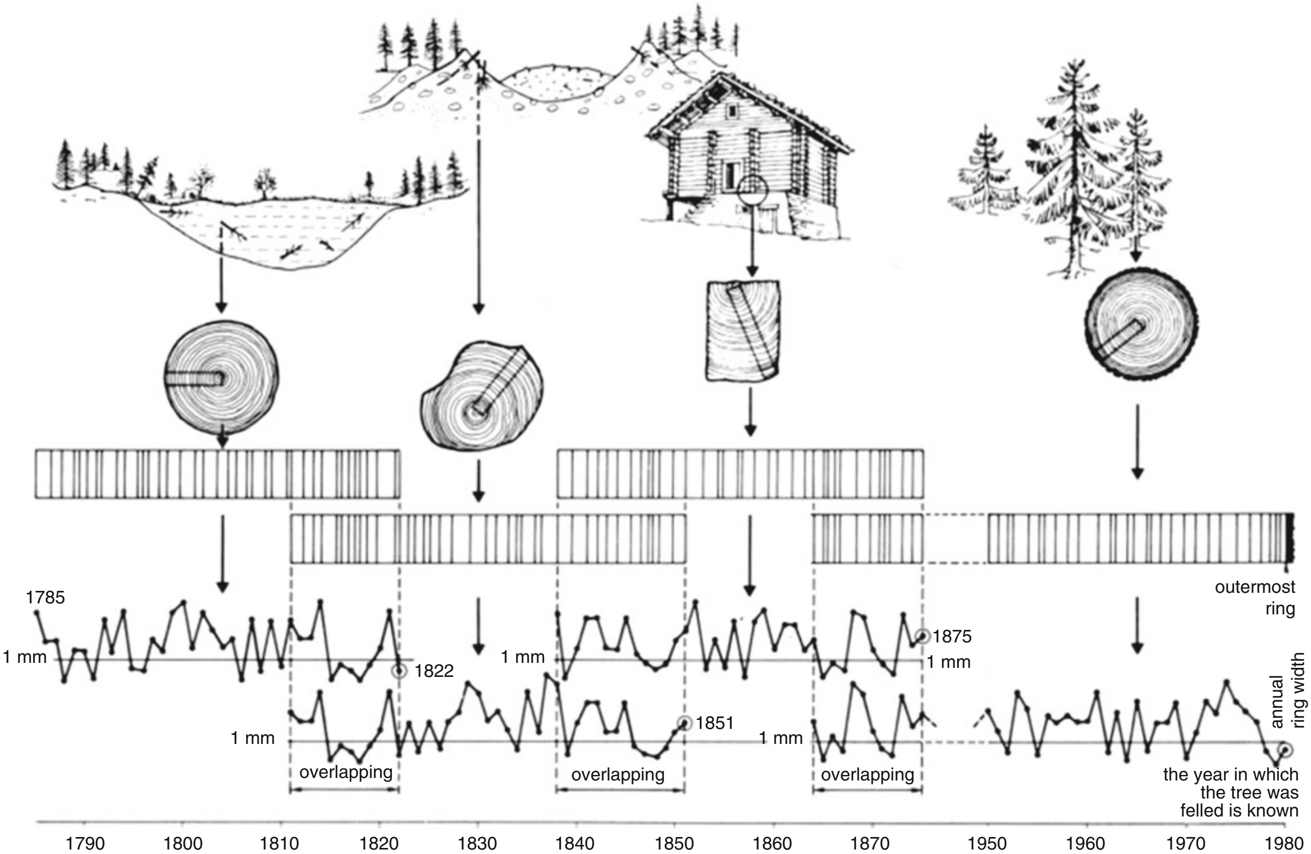
Measurements of tree-ring variables other than ring width are now common in dendrochronological research. Dendrochemistry (see section below), for example, can be employed to monitor historical changes in trace metal deposition. Once ring-width patterns are synchronized using standard dendrochronological techniques, cores can then be subsampled. These wood samples can then be digested in acid, and the resultant solutions are filtered and analyzed using techniques such as inductively coupled mass spectrometry (ICP-MS) (Watmough, 1999; Lageard et al., 2008). These additional analyses are costly in terms of time, money, and facilities. Tree-ring density has been identified as a surrogate for summer temperatures; hence, it is widely used in climatic reconstructions (see "Climate reconstruction (dendroclimatology)"). Density data can require complex sample preparation and costly measuring equipment (Schweingruber, 1988, 64–71), but image analysis and blue light reflectance are now thought to be a low-cost surrogate for ring density (McCarroll et al., 2002).

A rapidly expanding area within dendrochronology is the use of the isotopic composition of wood to reconstruct past climate. Physiological processes governing, for instance, oxygen isotope composition ($\delta^{18}O$) in wood are now generally well understood (McCarroll and Loader, 2004), and the widely acknowledged correlation between wood $\delta^{18}O$ and precipitation has driven reconstructions as far back as AD 1697 (Rinne et al., 2013).

Cross dating and chronology building

Tree-ring series from wood samples thought to have grown contemporaneously are compared using a technique known as cross dating – sometimes also referred to as cross matching. This is the procedure "for matching variations in ring-width or other ring characteristics among several tree ring series, allowing the identification of the exact year in which each tree ring was formed. . ." (Kaennel and Schweingruber, 1995, 81).

Matching tree-ring series can be achieved manually using skeleton plots (see "Measurement") or by comparing ring widths plotted on a semilogarithmic scale. Both methods place emphasis on narrow rings to aid

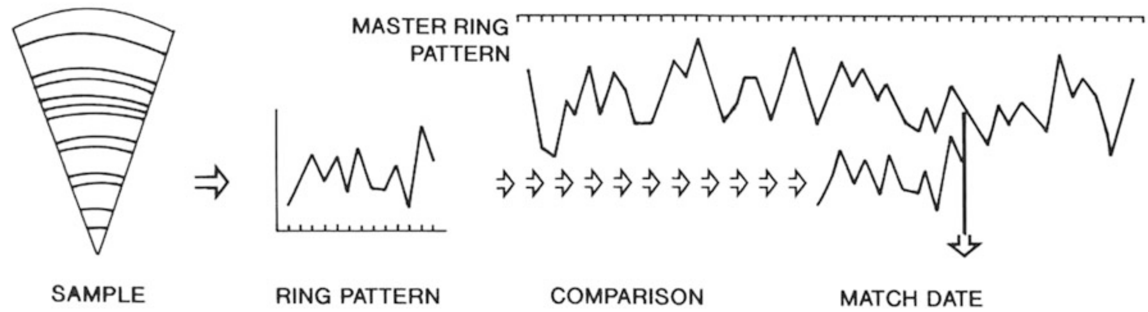


Dendrochronology, Figure 3 A visual representation of how tree-ring samples are cross-dated using the bridging technique (Reproduced from Schweingruber, 1983, 51 with permission).

comparisons. Due to the volume of data in modern research, mean ring-width measurements from individual trees or timbers are more frequently compared using specialist cross-matching software such as COFECHA (Holmes, 1983; Speer, 2010, 115–133) or DENDRO (Tyers, 1999). Cross-matching software contains routines that calculate statistically the strength of correlation between two ring-width series for a set of consecutive positions at which the two data sets could overlap. For instance, DENDRO utilizes t-value calculations based on routines published by Baillie and Pilcher (1973) and Munro (1983) to highlight positions where the two ring series might match. If the t-values exceed specified criteria, for example, $t > 3.5$, they are listed and form the basis for checking the reliability of correlations. Cross matching between two samples should always be verified by visual comparison of ring-width plots, as relatively high t-values (e.g., $t \geq 6.0$) can give spurious results.

Once exact contemporaneity between samples is established, sample means can be combined to produce an averaged tree-ring record or a tree-ring chronology. Chronologies are produced for living trees in a specific geographical or ecologically defined area, and they can be assigned calendar (chronometric) ages if careful note is made of the sampling dates of living trees. Chronologies from living trees can then be extended further back in time using wood that has been preserved in buildings or within preservative natural environments (e.g., anaerobic peat deposits). Tree-ring series from older sources of wood can be cross-dated with younger chronometrically dated records, extending the chronology of tree growth further back in time using the bridging technique illustrated in Figure 3. Tree-ring chronologies are normally made from wood samples of a single species. They can be created using several different parameters, such as ring width, maximum ring density, vessel size, or isotopic composition.

Once a chronology has been built, further statistical manipulation is possible. Such calculations include the expressed population signal (EPS), which measures the strength of common variability among the component records making up the chronology, and standardization, which maintains low-frequency variability within the data while removing age-related growth trends (Speer, 2010,



Dendrochronology, Figure 4 A schematic representation of the process leading to a dendro- or match date (From Baillie, (1995, 17) with permission).

141–142). Both EPS and standardization are considered essential in climate-related studies (see "Pollution: air and soil (dendrochemistry)").

Establishing a dendrodate

Over the last few decades, the work of dendrochronologists has been instrumental in creating a large geographical network of master chronologies largely based on ring-width measurements (Haneca et al., 2009). These master chronologies have then been used to date wood samples from natural and built environments using the software outlined above (as illustrated in Figure 4). This process seems straightforward, but there are a number of factors including minimum sample requirements, complacent growth, and irregular growth patterns (Cherubini et al., 2013) that can obviate a dendrodate.

Where an exact calendar age is assigned to a tree-ring series, different dating scenarios can arise, providing important distinctions in archaeological and other interpretations. The presence of bark can provide an exact year, and sometimes even season, in which felling or mortality occurred (Hillam et al., 1990). If bark is lacking but some sapwood rings are present, an estimated felling date or mortality date can be calculated (English Heritage, 1998). Samples lacking bark and sapwood can provide only a terminus post quem (date after which death occurred).

Applications

Tree-ring chronologies facilitate dating of wood sampled in natural and anthropogenic contexts, but dendrochronology has much more to offer than simply the calendrical dating of building timbers. Dendrochronology has now been applied in a number of subfields, from tracing movements of timber to studying the timing and impacts of past volcanic eruptions.

Archaeological dating (dendroarchaeology)

Dendrochronology is a widely used and accurate dating tool employed as an integral part of archaeological investigations (Baillie, 1982). In the American Southwest, dating both charcoal samples and beams used in building construction have provided a detailed understanding of the development of native Pueblo cultures (Nash, 1999; Speer, 2010). Recent developments in archaeological dating include chronology development from salvaged river logs (Dick et al., 2014).

Haneca et al. (2009) list some important European archaeological sites that have benefitted from routine tree-ring dating yet have also been instrumental in the development of the method. These include the Viking settlement of Haithabu (Hedeby, Germany; Eckstein, 1969; Eckstein and Wrobel, 2007), prehistoric lake shore settlements (pile dwellings) in the area surrounding the Alps (Billamboz, 1996, 2008), and the Neolithic Sweet Track in the UK dated to 3807/3806 BC (Hillam et al., 1990). Haneca et al. (2009) also note the success of routine dating for archaeological samples based on a dense network of chronologies that has been created in northern and western Europe following the development of long chronologies and the proliferation of dendrochronology laboratories, particularly since the 1990s. Tree-ring dating remains difficult in some areas, particularly southeast of the Alps (Italy, Slovenia, Austria), due to a lack of prehistoric chronologies (Haneca et al., 2009).

Widespread dating of both vernacular and more prestigious buildings (e.g., castles and cathedrals) during the historic period has revealed progression in architectural styles over time, unknown construction or repair phases, and the stockpiling of wood for prestigious building projects (Hillam and Groves, 1996; Hoffsummer, 2002; Miles, 2006).

Exciting developments related to the use of dendrochronology in archaeological dating are the dating and provenancing of shipwrecks (cf. Čufar et al., 2014; Nayling and Susperregi, 2014) and the reconstruction of past forest management practices.

Sourcing timber (dendroprovenancing)

Dendrochronology in Europe has developed regionally with chronologies being constructed and wood dated at local and regional levels. As the geographical coverage of chronologies expanded, cross matching and cross dating of wood became possible over greater distances, but there were still limits to this based on the fact that tree growth responses are governed by regional climates and environmental conditions. For example, cross matching is often possible between England and Ireland, but not between Ireland and Germany or between England and Poland. Haneca et al. (2009, 6) capture the essence of these relationships in their definition of dendroprovenancing:

> Trees experiencing similar growth conditions are expected to develop a comparable ring-width pattern. This is one of the basic principles of dendrochronology. Trees from distant geographical locations will develop growth ring patterns with different characteristics, driven by discrepancies in the local climate and site conditions. This supports the assumption that a tree-ring pattern contains information related to the location at which the tree grew. Comparison of individual tree-ring series with chronologies that reflect the average growth conditions for specific regions allows the sourcing of the origin of the timber, i.e., dendro-provenancing.

The proliferation of European oak chronologies in the 1980s opened up the possibility of unraveling significant problems that had previously been encountered in tree-ring dating. Cases in point were the art-historical oak chronologies created in the 1970s. Medieval paintings were often made on thin oak boards or panels. Attempts to date these by measuring oak ring-width series and comparing them to oak chronologies constructed from local timber sources often failed. It was suspected that the oak boards may have come from more distant locations (Baillie, 1995; Eckstein and Wrobel, 2007). Creation of a Gdańsk-Pomerania chronology by Wazny (Eckstein et al., 1986) was key to dating wood used in creating Dutch paintings and also wooden artifacts from Lübeck Cathedral, separating German timber from Baltic timber sources (Eckstein and Wrobel, 2007). The medieval Baltic timber trade has also been revealed in imports of wood used for construction purposes in the British Isles, as at Stirling Castle, Scotland (Crone and Fawcett, 1998; Mills and Crone, 2012). Art-historical oak wood in Europe is now routinely dated using Polish and Baltic reference chronologies (Haneca et al., 2005).

Perhaps the most often quoted example of dendroprovenancing is the case of the Skuldelev ships, which were excavated in a Danish fjord between AD 1958 and 1962. These included warship, trading, and fishing vessels that were clearly of Viking age in their construction, yet their oak tree-ring series did not cross-match against any German or Scandinavian chronologies. Some aspects of their design hinted at a possible British origin of the wood, and subsequent comparisons with English and Irish chronologies showed highest correlations with a chronology constructed from trees that had grown in the Dublin area (Ireland). This led to the conclusion that Vikings who had settled in Ireland constructed the ships from Irish oak around AD 1060, before sailing them back to Denmark (Bonde and Crumlin-Pedersen, 1990; Baillie, 1995).

Tree-ring chronologies now form a dense geographical coverage, particularly in northern Europe, affording the possibilities of high-resolution dendroprovenancing (e.g., Daly and Nymoen, 2008). Such studies may, however, suggest more than one possible timber origin, so the results of attempted dendroprovenancing are not always easily interpreted (Bridge, 2011, 2012). Nevertheless, tree-ring research focusing on dendroprovenancing is an increasingly important area within dendrochronology.

Sources of wood transported by rafting on rivers in central and northern Europe (for charcoal used in the production of iron) have been traced by Grabner et al. (2004). In southern Germany, the altitudinal sensitivity of growth in spruce (*Picea abies*) and fir (*Abies alba*) has permitted the provenancing of rafted logs to specific mountain areas (Dittmar et al., 2012). Dendroprovenancing can also play a critical role in evaluating the relative integrity of historic buildings (Sass-Klaassen et al., 2008). In addition to ring-width measurement, elemental and isotopic analyses of tree rings have added important new dimensions in dendroprovenancing (Durand et al., 1999; Reynolds et al., 2005; Kagawa and Leavitt, 2010).

Dendroecology

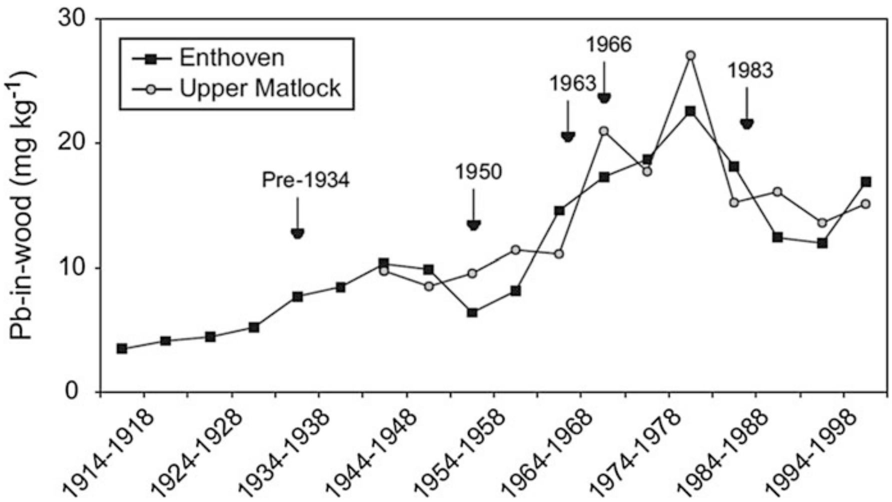
Dendroecology is a subfield of dendrochronology and encompasses all the other subfields that use dated tree rings to study ecological problems and the environment (Kaennel and Schweingruber, 1995). Examples of other subfields include dendrochemistry, dendroclimatology, dendrogeomorphology, dendrohydrology, dendroglaciology, dendrovolcanology, and a number of subfields that assist informed forest management – all covered in the sections below.

Pollution: air and soil (dendrochemistry)

Dendrochemistry has been defined as "…the use of tree rings as indicators of past chemical fluctuations in the environment" (Cutter and Guyette, 1993, 612). It has been widely employed in attempts to reconstruct pollution histories and also in the calibration of the radiocarbon (^{14}C) timescale.

Pollution directly resulting from human activities is known to have a detrimental impact on trees, causing tree mortality especially for those growing in close proximity to industrial plants (Schweingruber, 1996). The key question is whether dendrochronology can be used to reconstruct annual fluctuations in pollutants accurately.

A number of issues and potential problems exist in dendrochemical research, including (1) species suitability, (2) pollution pathways (leaves, needles, bark, or roots), (3) the effects of soil acidity on elemental uptake (cf. Guyette et al., 1991), (4) elements essential or nonessential for growth, (5) radial translocation within wood (cf. Watmough and Hutchinson, 2002), (6) tree age, (7) variations in elemental concentrations in trees sampled close together, and (8) potential chemical contamination of increment cores. These difficulties led Smith and



Dendrochronology, Figure 5 Dendrochemical records from Scots pine (*Pinus sylvestris*) sampled near a lead smelter (*black squares*) and trees from a sampling site 9 km distant (*gray circles*) in the Peak District, Derbyshire, UK (From Lageard et al., 2008, with permission).

Shortle (1996, 633) to write "...radial trends of chemical data are not good places to 'go fishing' for research topics."

Nevertheless, if careful consideration is given to potential shortfalls in designing research projects (Watmough, 1999), successful pollution reconstructions are thought to be possible (Lageard et al., 2008), and these can shed light on the scale of human impacts upon the environment in industrial archaeology. Figure 5 shows dendrochemical records obtained from Scots pine (*Pinus sylvestris*) growing adjacent to, and at 9 km distant from, a lead smelter in Derbyshire, UK. These records mirrored anticipated pollution trends based on industrial output and on increasing use of mitigation technologies. Other studies have concluded that accurate pollution reconstructions were impossible for combinations of the factors listed above (e.g., Patrick and Farmer, 2006).

Measurements of isotopic variations in wood that has been used in the construction of long chronometrically dated tree-ring chronologies in Europe and North America have also provided records of natural variations in the production of radiocarbon (^{14}C) that are now routinely applied in the calibration of radiocarbon dates (Walker, 2005, 32–36).

Climate reconstruction (dendroclimatology)

Climate is "...one of the main controlling factors of most tree-ring growth across all spatial and temporal scales" (Speer, 2010, 174). Several approaches have been adopted in order to reconstruct past climate and its effects on trees and their spatial distributions. These include (1) calibrating growth responses with meteorological data and (2) studying growth responses or the presence/absence of trees related to present-day latitudinal and altitudinal growth limits.

Dendroclimatic reconstructions seek to establish a link between specific climatic variables and tree growth, usually through statistical comparisons of tree-ring and meteorological data. Generally, standard field and laboratory methods are employed, but careful attention is required for climatically sensitive site selection, tree age, number of samples (Speer, 2010), and the need for removal of age-related growth trends (standardization). The climate response of trees is achieved using a correlation matrix, or response function analysis, to compare the master chronology with monthly climate data to identify months or seasons that correlate with ring-width data. Calibration then occurs as a transfer function (Fritts, 1976), describing the relationship between the tree rings and climate variables using linear regression analysis. Transfer function coefficients are used to transform, or rescale, the tree-ring sequence into a new sequence of meteorological estimates that can be extended back in time for the whole length of the tree-ring sequence (Schweingruber, 1988). The final stage is verification, when the validity of the model is tested by comparing reconstructed climatic data with real data that have not been used in the calibration.

Examples of dendroclimatic reconstructions based on different tree-ring parameters include Briffa et al. (2001), who reconstructed summer temperatures for the northern boreal forest over the previous 600 years based on ring density, and Rinne et al. (2013), who utilized $\delta^{18}O$ isotope measurements to reconstruct precipitation back to AD 1697.

Climatic reconstructions can also be achieved using routine dendrochronological techniques. For example, Shumilov et al. (2007) studied juniper (*Juniperus sibirica*) on the Kola Peninsula, Russia, using ring-width analyses, establishing a 676-year chronology. This record correlated well with known periods of reduced solar radiation (Sporer, Maunder, and Dalton minima) and associated decreases in hemispheric temperatures. Subfossil larch (*Larix sibirica*) has also been used in latitudinal reconstruction of climatically induced latitudinal fluctuations in the northern boreal tree line (Hantemirov and Shiyatov, 2002), and the altitudinal limit of stone pine (*Pinus cembra*) was reconstructed by Nicolussi et al. (2005) in the Austrian Alps, during the last ca. 9,000 years using living trees and subfossil samples retrieved from till in glacier forefields. Neuwirth et al. (2007) employed the more traditional pointer year approach (Schweingruber et al., 1990) in conjunction with GIS to identify spatial patterns in positive and negative growth anomalies evident in 377 ring-width chronologies from central Europe. Pointer years are cross-dated years in which the majority of trees investigated have responded simultaneously to events such as the Europe-wide drought experienced in AD 1976.

As climatic reconstructions have become more widespread, it is now possible to map the effects of specific climatic variables across regions and continents to create dendroclimatological networks (cf. Fritts, 1976). Esper et al. (2009) used 53 ring width and 31 maximum latewood density chronologies across Northern Eurasia to establish an east-west climatic gradient and a correlation between larch (*Larix decidua*) and temperature. D'Arrigo and Jacoby (1991) found links between El Niño and climate in the Southwestern United States. North Atlantic Oscillation sea surface temperature signatures are also apparent in tree-ring records of Scandinavian pine (*Pinus sylvestris*) chronologies (D'Arrigo et al., 1993).

The impacts of major climatic events on human populations have been clarified through tree-ring-based reconstructions (Jacoby et al., 1999; Stahle et al., 2000). Chronology building itself has also encountered periods where few dated samples are available (Baillie, 1995), thought originally to be artifacts of sampling strategies. These may, in fact, be genuine "gaps" related to climatic downturns or other factors such as disease that have impacted human populations as well as trees (Brown and Baillie, 2012).

Application of dendrochronology to climate has been "One of the most publically debated applications of dendrochronology" (Speer, 2010, 174). This statement referred primarily to the controversial "hockey stick" multi-proxy climate reconstruction of Mann et al. (1998) that provided early scientific evidence in support of global warming exacerbated by human industrial activity (IPCC, 2007). Dendroclimatology and its statistical methods again came under international scrutiny in 2009 with "Climategate" (Carrington, 2011) in which hacked email messages of the Climate Research Unit at the University of East Anglia, UK, were exploited to cast doubt on the human agency behind climate change.

Recent dendroclimatological research has identified hydroclimatic events of great magnitude and duration in central Europe that may have had significant past political consequences. Büntgen et al. (2011) argue that these should serve as historical justification for expenditure in advance of currently projected climate change.

Slope instability (dendrogeomorphology)

This subfield of dendrogeomorphology has been defined as "The use of tree rings to date geological [sic geomorphological] processes that affect tree growth" (Speer, 2010, 219). Its significance in geoarchaeology is that it can help in developing an understanding of how natural processes can influence human activities, notably settlements, and how natural processes can also affect archaeological sites, particularly those that were abandoned and then colonized by trees. Schweingruber (1996, 272) noted that dendrochronology had rarely been considered in mountain forests where geomorphological processes are common and stated that "only dendrochronology is able to provide information about the frequency and extent of past events."

Trees react in a number of ways to the onset of slope instability or instability caused by other processes, for example, advancing ice ("Impact of ice (dendroglaciology)," see below). Onset dates, years, or sometimes seasons can be identified from a variety of evidence preserved in tree-ring records such as: the formation of reaction wood (see "Living trees") in response to trees starting to lean; scars left following damage to the bark and cambium; root exposure; tree mortality, and tree establishment germination dates (ecesis, or colonization of a new habitat by a species). Although the principles of dendrogeomorphology were established in the 1970s (Alestalo, 1971; Shroder, 1978), research in this area has only recently proliferated, benefitting from advances in dendrochronological techniques and computer technology. For instance, Stoffel et al. (2005) made detailed analyses of the impacts of rock falls in the Swiss Alps on European larch (*Larix decidua*). In addition to dendrochronological dating, the authors used GIS software to visualize the spatial extent, as well as the timing of events. Such studies have important implications for reconstructing past mass movement activity and are key tools in hazard mapping and hazard mitigation. Similar research has been undertaken for different types of mass movement, such as debris flows (Bollschweiler et al., 2008; Sorg et al., 2010).

Dendrogeomorphology also includes research with the goals of dating lakeshore erosion (Fantucci, 2007), tectonic movements such as earthquakes (Jacoby et al., 1997), and the buildup of coarse wood debris (Campbell and Laroque, 2007).

Impact of water (dendrohydrology)

"Dendrohydrology uses dated tree rings to study and date hydrologic phenomena, such as river flow, lake level changes and flooding history" (Kaennel and Schweingruber, 1995, 71). Trees growing in a variety of landscapes from upland to lowland can be affected by hydrological events. For instance, trees bordering streams and rivers can be uprooted by flood events, tilted as soils and banks are washed away, or scarred by debris carried by flood water. Subfossil trees preserved in sediments marking old river courses in central Europe have been a key resource in building long master chronologies (Becker, 1993).

Dating scars and abrupt growth changes allow a temporal and spatial assessment of the disturbance regime. Zielonka et al. (2008) reconstructed flood history in the Tatra Mountains, Poland, using cross-dated scars from trunks of Norway spruce (*Picea abies*). Flood events identified in the tree-ring sequence were compared to meteorological data, and although no one variable could be held responsible for all the flooding, the dendrochronological approach identified otherwise invisible flood events. Trees can also be defoliated during flooding, which can affect wood structure as demonstrated for young ring-porous ash trees (*Fraxinus americana* and *F. pennsylvanica*) by Yanosky (1983). Erosion during flood events can cause sediment loss and root exposure, leading to growth reductions, tree destabilization, and the formation of compression and tension wood. In riverbeds, undermined trees often lean in the direction of water flow. Sediment deposited by floods can lead to the growth of adventitious roots and shoots (the development of secondary cambium on older stems, branches, and roots), both of which can be dated to establish timing of their response to flood events. As flows subside, trees germinate in locations protected from water flow, for example, on the downstream side of boulders. Riverbed trees can provide minimum ages since the last major flood event (Schweingruber, 1996, 133).

In colder climates, ice can scar trees on river banks (Payette and Delwaide, 1991) and lakeshores. Research focused on the latter has used combinations of ice scars and tension wood resulting from tree tilting by waves to reconstruct higher water levels and to make inferences about increased flooding events and climate change (Bégin, 2001). In more arid areas, tree rings of bristlecone pine at lower elevations have been shown to be sensitive to the combined effects of precipitation and evapotranspiration. In a hydroclimatic reconstruction, Woodhouse et al. (2011) were able to estimate water flow in the Arkansas River (USA) from AD 1275 to 2002.

Génova et al. (2011) investigated small wooden "canals" used to channel river flow and to drive machinery of the sixteenth-century Old Mint in Segovia, Spain. Dendrochronology was used to date timbers used in repairs following flood events, and these data were compared to documentary records to confirm the timing of flood events, to assess their relative magnitude, and also to identify undocumented floods. Dean (1993), studying canyon terraces in Arizona, USA, successfully employed geological and archaeological analyses together with tree-ring dating to reconstruct landscape history.

Groundwater levels can have significant effects on trees. Although species demonstrate different tolerances to water in soil (cf. Vreugdenhil et al., 2006), prolonged waterlogging will often lead to significant growth reductions and eventually tree mortality.

Peat bogs are naturally wet places, but during drier periods, they can be colonized by trees. Layers of mire-rooting woodland have been uncovered, usually during commercial peat extraction, and dendrochronological investigations have now produced chronometrically dated ring-width sequences that demonstrate distinct periods of germination (ecesis) and mortality during the Holocene associated with climate-driven hydrological variations on bog surfaces (cf. Eckstein et al., 2010). In coastal areas, often rich in archaeology, salt water incursions caused by postglacial sea-level rise have been responsible for woodland mortality of submerged coastal forests on the Dutch coast (Munaut, 1966) and of the intertidal woodland and associated Mesolithic and Neolithic archaeology of the Gwent Levels, South Wales (Bell et al., 2001).

Deliberate human interventions in the landscape can improve conditions for tree growth through drainage (Schulthess, 1990). Conversely, artificial aridity can be detrimental to tree growth as exemplified by solution mining. In the hydrogeological research documented by Lageard and Drew (2008), the growth responses of oak (*Quercus robur*) were shown to be governed by water-table variations resulting from brine pumping in the Cheshire Saltfield, UK (Figure 6). Significant reductions in ring widths could be related to the construction of brine processing sites in the 1920s and precisely to the cessation of all pumping activities in AD 1977.

Impact of ice (dendroglaciology)

Dendroglaciology is the use of tree-ring series to date and plot the extent of past glacier movements, defined by relic landscape features such as moraines and trimlines. This subfield has close affinities to dendroecology and dendrogeomorphology, as trees react to ice advances and retreats in forested areas by (1) being scarred or killed by ice advances, (2) tilting under the impact of ice advance, and (3) colonizing glacier forefields upon ice retreat. In Europe, the rate at which different species colonize freshly de-glaciated land (ecesis) has been studied in localities such as the Aletsch Glacier in Switzerland, where colonization by spruce (*Picea abies*) and larch (*Larix decidua*) took on average 20 years, whereas stone pine (*Pinus cembra*) took 45–85 years (Schweingruber, 1988).

Classic dendroglaciological research has mapped the maximum extent of Little Ice Age outlet glaciers emanating from the Columbia Icefield in the Canadian Rockies (Luckman, 1988). It has also reconstructed glacial mass balance (inputs and outputs to glacial systems), for example, a 600-year reconstruction in the Austrian Tyrol (Nicolussi and Patzelt, 1996) and a 400-year reconstruction using hemlock (*Tsuga mertensiana*) for two glaciers on Vancouver Island, western Canada (Lewis and Smith, 2004). Further information on the history of, and techniques employed in, dendroglaciology is available in Smith and Lewis (2007).

Dendrochronology, Figure 6 Surface depressions resulting from uncontrolled solution mining of salt and the collapse of underground cavities in Cheshire, UK: (**a**) subsidence lake or "flash" and (**b**) a possible "brine run" resulting from solution of salt beds at depths of ca. 30–40 m. Such landscape features as in (**a**) document hydrological change that can impact tree growth, while the latter (**b**) can document the environmental impacts of industry (Images: J. Lageard).

Volcanic impacts (dendrovolcanology)

There are a number of ways in which volcanic eruptions/ episodes can affect tree growth. Tree mortality can be caused by shock or heat waves, by hydrological change (as volcanic sediments can cause prolonged flooding), or through natural pollution (SO_2, fumaroles). Growth suppression can result from the proximity to lava flow causing tree tilting, scorched crowns, dust-reducing photosynthesis, responses to burial by volcanic sediments, and volcaniclastic sediment preventing germination. Volcanic impacts can conversely improve tree growth when the death of emergent trees leads to subsequent growth release in trees of the previously suppressed understory. Fine volcanic ash, in contrast to coarser volcaniclastics, promotes rapid seed germination (Schweingruber, 1996).

Dendrochronology can therefore be used to study the environmental impacts of volcanism and also to date specific events during the historic period when documentary evidence does not exist. For example, Yamaguchi et al. (1990) dated the extrusion of the large andesite "Floating Island" lava flow at Mount St. Helens, USA, to late AD 1799 or early AD 1800 using living trees, and Yadav (1992) reconstructed regional volcanism on the Kamchatka Peninsula, Russia. Jacoby et al. (1999) demonstrated major human impacts on the Alaskan Inuit following the eruption of Laki in AD 1783.

Volcanic events can also be dated by sudden growth reductions preserved in timber, such as a beam from Wupatki, Arizona (USA), thought to date an eruption of Sunset Crater to AD 1064 (Smiley, 1958). Similar growth reductions can also appear within subfossil tree-ring series from prehistory. Contemporaneous narrow ring events (NREs), found in bog oaks preserved in natural environments such as peat bogs throughout northern and western Europe, are thought to indicate long-term climatic cooling, so-called volcanic winters, caused by the prolonged presence of volcanic aerosols in the atmosphere (Baillie, 1995). Chronologies based on ring density have also clearly demonstrated the climatic impacts of volcanism on summer temperatures during the historic period (Briffa, 2000).

Dendrovolcanology is, however, not without its controversy. Narrow rings in European bog oaks supported by the simultaneous appearance of frost rings in bristlecone pines (LaMarche and Hirschboeck, 1984) have provided a chronometric date for the catastrophic Bronze Age eruption of the Greek Island of Santorini, 1628 BC (Baillie and Munro, 1988; Baillie, 1995). This date depends upon the Santorini eruption having had global climate effects. Problems have occurred with attempts to correlate a tree-ring date such as this with loosely dated environmental evidence, for instance, acidity layers preserved within ice cores (Baillie, 1991). The 1628 BC date continues to generate controversy (Zielinski and Germani, 1998), not due to the emotive links made by some to the legend of Atlantis but because varied specialists still find it challenging to link tree ring and ^{14}C determinations that indicate a date in the seventeenth century BC with the associated artifacts that appear to belong to a period over 100 years later. Similar debates have arisen concerning other notable prehistoric eruptions, such as Hekla 3 in Iceland with a dendrodate of 1159 BC, when scientists try to make links with other paleoecological records loosely dated by radiocarbon, such as those obtained from pollen analysis (Payne et al., 2013).

Volcanoes are not the only environmental mechanism capable of causing sudden climate change and prolonged growth reductions in trees. The AD 540 NRE has been linked to the effects of specific volcanoes, but the dating evidence (^{14}C) is inconclusive, and it is possible that a meteorite strike similar or greater than that experienced at Tunguska (Siberia) in AD 1908 could have caused significant disruption to the Earth's atmosphere over a number of years (Baillie, 1995, 91–107).

Forest management

Dendrochronological research has been used increasingly by foresters in the management of woodland resources, for instance, in assessing the role of fire in the landscape (dendropyrochronology), damage caused by insects (dendroentomology), and also changes in species composition. Humans are key agents of change in forests and woodlands, and as such, dendrochronological reconstructions of the extent and composition of forested areas are of relevance to archaeology, particularly in understanding the evolution of cultural landscapes.

Schöne and Schweinguber (2001) used dendrochronological techniques to reconstruct the history of natural reforestation in the Inn Valley, Switzerland, since World War II following land abandonment in response to changing management practices and rural-urban migration. Such abandonment often results in reduced biodiversity, as highlighted in Sweden when traditional medieval farming practices lapsed (Hayashida, 2005). In these abandoned landscapes, older trees, originally retained for practical, cultural, and aesthetic reasons, often remain concentrated around villages as relict features. Combinations of dendrochronological data and information gleaned from other sources, such as forest management records (Müllerová et al., 2014) and livestock inventories (Genries et al., 2009), can be used to reconstruct land use history and also to make informed choices regarding conservation management. There is also potential for similar dendrochronologically informed reconstructions in former industrial landscapes and in relict battlefield landscapes, for example, in parts of the European Alps fought over in the First World War (Thompson, 2008). In the future, dendrochronology could play an important role in multi-proxy archaeo-environmental studies attempting to shed more precise light on significant military deforestations already apparent in palynological (Dumayne and Barber, 1994; Dumayne-Peaty, 1998) and documentary research (Pluskowski et al., 2011).

Trees can be affected by fire of both natural and human origin. Tree mortality will result if the bark and cambium are killed around the full circumference of the trunk, but some tree species, notably pines (Richardson, 2000; Lageard et al., 2000), have developed resistance to fire and protect damaged areas of the trunk by producing callus tissue and forming a scar (Schweingruber, 1988, 206). In fire-prone regions, a series of fires can burn into a tree leaving a set of overlapping scars and sometimes a large triangular scarred area at the base of the trunk known as a catface (Speer 2010, 197). In some species, the impacts of fire may be more subtle and noted only by carefully documenting anomalous wood structure, for instance, in black ash *Fraxinus nigra* (Kames et al., 2011). Scars can be sampled from living and dead trees by cutting discs or partial sections using a chainsaw (Arno and Sneck, 1977). Once prepared using standard techniques, these samples can be dated by dendrochronology to calendar years, seasons, or even parts of seasons – as illustrated by Swetnam and Baisan (1996). Records of fire scars in individual trees can be synchronized in fire history charts to document regional fires over prolonged periods (Swetnam et al., 1999) and the calculation of fire return intervals. The latter can be related to human interventions, and the significance of fire as a management tool can be seen, for instance, in its use by Native Americans to favor mast-producing trees (those yielding edible nuts) such as oak, hickory, chestnut, and walnut. These management practices are thought to have had a major impact on the distributions of present-day forest and grassland ecosystems of the eastern USA (Abrams and Nowacki, 2008). Dendrochronology now also provides the scientific basis for fire suppression policies in the USA that became prevalent in the later twentieth century, as foresters and politicians struggled to combat the effects of fire on humans and their habitations (Speer, 2010).

Summary and future directions

Dendrochronology is a powerful chronometric dating technique that has been employed in many research projects that can be linked directly or indirectly to geoarchaeology. The technique has its limitations in terms of suitability of tree species, suitability of sampling sites, and minimum sample requirements for computer-assisted cross matching. That said, the technique has been applied in numerous environments, both natural and those affected by humans.

Traditionally, dendrochronology has been applied in the dating of wood from archaeological sites and from standing buildings, but the technique has much wider application and also potential. Of particular relevance to geoarchaeology is the use of dendroprovenancing that can reconstruct historic and potentially prehistoric movements of timber from forest source regions, reconstruction of past land use, industrial and pollution histories, and climatic reconstructions that can be used to assess climatic/environmental impacts on past and future human population.

Baillie (1995, 32) sums up the significance of the technique: “The power of dendrochronology to date things precisely opens up a whole new window into the past. . ..” The utility and future directions of the technique are often discussed at conferences (Baillie, 2002; Sass-Klaassen, 2002). Some important themes in this respect have included the handling and storage of increasingly large quantities of data (Jansma et al., 2012); improving dendrochronological coverage, spatially and temporally; dendroprovenancing; the use of tree rings as sources of environmental data; funding for academic and private laboratories; cooperation between dendrochronology and other disciplines; and also the need for dendrochronology to receive proper recognition as an interdisciplinary subject in academia.

Bibliography

Abrams, M. D., and Nowacki, G. J., 2008. Native Americans as active and passive promoters of mast and fruit trees in the eastern USA. *The Holocene*, **18**(7), 1123–1137.

Alestalo, J., 1971. Dendrochronological interpretation of geomorphic processes. *Fennia*, **105**(1), 1–140.

Arno, S. F., and Sneck, K. M., 1977. *A Method for Determining Fire History in Coniferous Forests of the Mountain West. General Technical Report INT-42*. Odgen: Intermountain Forest and Range Experiment Station, Forest Service, US Department of Agriculture.

Babiński, L., 2011. Investigations on pre-treatment prior to freeze-drying of archaeological pine wood with abnormal shrinkage anisotropy. *Journal of Archaeological Science*, **38**(7), 1709–1715.

Baillie, M. G. L., 1982. *Tree-Ring Dating and Archaeology.* Chicago: University of Chicago Press.

Baillie, M. G. L., 1991. Suck in and smear: two related chronological problems of the 90s. *Journal of Theoretical Archaeology*, **2**, 12–16.

Baillie, M. G. L., 1995. *A Slice Through Time: Dendrochronology and Precision Dating*. London: Batsford.

Baillie, M. G. L., 2002. Future of dendrochronology with respect to archaeology. *Dendrochronologia*, **20**(1–2), 69–85.

Baillie, M. G. L., and Munro, M. A. R., 1988. Irish tree rings, Santorini and volcanic dust veils. *Nature*, **332**(6162), 344–346.

Baillie, M. G. L., and Pilcher, J. R., 1973. A simple cross-dating program for tree-ring research. *Tree-Ring Bulletin*, **33**, 7–14.

Becker, B., 1993. An 11,000-year German oak and pine dendrochronology for radiocarbon calibration. *Radiocarbon*, **35**(1), 201–213.

Bégin, Y., 2001. Tree-ring dating of extreme lake levels at the subarctic–boreal interface. *Quaternary Research*, **55**(2), 133–139.

Bell, M., Allen, J. R. L., Nayling, N., and Buckley, S., 2001. Mesolithic to Neolithic coastal environmental change c. 6500–3500 cal BC. *Archaeology of the Severn Estuary*, **12**, 27–53.

Bernabei, M., Bontadi, J., and Rognoni, G. R., 2010. A dendrochronological investigation of stringed instruments from the collection of the Cherubini conservatory in Florence, Italy. *Journal of Archaeological Science*, **37**(1), 192–200.

Bill, J., Daly, A., Johnsen, Ø., and Dalend, K. S., 2012. DendroCT – dendrochronology without damage. *Dendrochronologia*, **30**(3), 223–230.

Billamboz, A., 1996. Tree rings and pile-dwellings in southern Germany: following in the footsteps of Bruno Huber. In Dean, J. S., Meko, D. M., and Swetnam, T. W. (eds.), *Tree Rings, Environment and Humanity: Proceedings of the International Conference, Tucson, Arizona, 17–21 May 1994*. Tucson: Radiocarbon, Department of Geosciences, University of Arizona, Tucson, pp. 471–483.

Billamboz, A., 2008. Dealing with heteroconnections and short tree-ring series at different levels of dating in the dendrochronology of the Southwest German pile-dwellings. *Dendrochronologia*, **26**(3), 145–155.

Bollschweiler, M., Stoffel, M., and Schneuwly, D. M., 2008. Dynamics in debris-flow activity on a forested cone – a case study using different dendroecological approaches. *Catena*, **72**(1), 67–78.

Bonde, N., and Crumlin-Pedersen, O., 1990. The dating of Wreck 2, the longship, from Skuldelev, Denmark. *NewsWARP*, **7**, 3–6.

Bridge, M., 2011. Resource exploitation and wood mobility in northern European oak: Dendroprovenancing of individual timbers from the Mary Rose (1510/11–1545). *The International Journal of Nautical Archaeology*, **40**(2), 417–423.

Bridge, M., 2012. Locating the origins of wood resources: a review of dendroprovenancing. *Journal of Archaeological Science*, **39**(8), 2828–2834.

Briffa, K. R., 2000. Annual climate variability in the Holocene: interpreting the message of ancient trees. *Quaternary Science Reviews*, **19**(1–5), 87–105.

Briffa, K. R., Osborn, T. J., Schweingruber, F. H., Harris, I. C., Jones, P. D., Shiyatov, S. G., and Vaganov, E. A., 2001. Low-frequency temperature variations from a northern tree ring density network. *Journal of Geophysical Research, [Atmospheres]*, **106**(D3), 2929–2941.

Brown, P. M., 2007. A modified increment borer handle for coring in locations with obstructions. *Tree-Ring Research*, **63**(1), 61–62.

Brown, D. M., and Baillie, M. G. L., 2012. Confirming the existence of gaps and depletions in the Irish oak tree-ring record. *Dendrochronologia*, **30**(2), 85–91.

Büntgen, U., Tegel, W., Nicolussi, K., McCormick, M., Frank, D., Trouet, V., Kaplan, J. O., Herzig, F., Heussner, K.-U., Wanner, H., Luterbacher, J., and Esper, J., 2011. 2500 years of European climate variability and human susceptibility. *Science*, **331**(6017), 578–582.

Campbell, L. J., and Laroque, C. P., 2007. Decay progression and classification in two old-growth forests in Atlantic Canada. *Forest Ecology and Management*, **238**(1–3), 293–301.

Carrington, D., 2011. Climategate: hacked climate science emails. *The Guardian online*. http://www.theguardian.com/environment/2010/jul/07/climate-emails-question-answer

Cherubini, P., Humbel, T., Beeckman, H., Gärtner, H., Mannes, D., Pearson, C., Schoch, W., Tognetti, R., and Lev-Yadun, S., 2013. Olive tree-ring problematic dating: a comparative analysis on Santorini (Greece). *PLoS ONE*, **8**(1), e54730. Open access.

IPCC (Intergovernmental Panel on Climate Change), (2007). Climate change 2007: working group I: the physical science basis. http://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch6s6-6.html

Cook, E. R., and Kairiukstis, L. A. (eds.), 1990. *Methods of Dendrochronology: Applications in the Environmental Science*. Dordrecht: Kluwer Academic.

Crone, A., and Fawcett, R., 1998. Dendrochronology, documents and the timber trade: new evidence for the building history of Stirling Castle, Scotland. *Medieval Archaeology*, **42**, 68–87.

Čufar, K., Merela, M., and Erič, M., 2014. A Roman barge in the Ljubljanica river (Slovenia): wood identification, dendrochronological dating and wood preservation research. *Journal of Archaeological Science*, **44**, 128–135.

Cutter, B. E., and Guyette, R. P., 1993. Anatomical, chemical, and ecological factors affecting tree species choice in dendrochemistry studies. *Journal of Environmental Quality*, **22**(3), 611–619.

D'Arrigo, R. D., and Jacoby, G. C., 1991. A 1000-year record of winter precipitation from northwestern Mexico, USA: a reconstruction from tree-rings and its relation to El Niño and the Southern Oscillation. *The Holocene*, **1**(2), 95–101.

D'Arrigo, R. D., Cook, E. R., Jacoby, G. C., and Briffa, K. R., 1993. NAO and sea surface temperature signatures in tree-ring records from the North Atlantic sector. *Quaternary Science Reviews*, **12**(6), 431–440.

Daly, A., and Nymoen, P., 2008. The Bøle ship, Skien, Norway – research history, dendrochronology and provenance. *The International Journal of Nautical Archaeology*, **37**(1), 153–170.

De Ridder, M., Trouet, V., Van den Bulcke, J., Hubau, W., Van Acker, J., and Beeckman, H., 2013. A tree-ring based comparison of *Terminalia superba* climate–growth relationships in West and Central Africa. *Trees*, **27**(5), 1225–1238.

Dean, J. S., 1993. Geoarchaeological perspectives on the past: chronological considerations. In Stein, J. K., and Linse, A. R. (eds.), *Effects of Scale on Archaeological and Geoscientific Perspectives*. Boulder: Geological Society of America. Geological Society of America Special Paper 283, pp. 59–65.

Dick, M., Porter, T. J., Pisaric, M. F. J., Wertheimer, È., deMontigny, P., Perreault, J. T., and Robillard, K.-L., 2014. A multi-century eastern white pine tree-ring chronology developed from salvaged river logs and its utility for dating heritage structures in Canada's National Capital Region. *Dendrochronologia*, **32**(2), 120–126.

Dittmar, C., Eißing, T., and Rothe, A., 2012. Elevation-specific tree-ring chronologies of Norway spruce and silver fir in southern Germany. *Dendrochronologia*, **30**(2), 73–83.

Dumayne, L., and Barber, K. E., 1994. The impact of the Romans on the environment of northern England: pollen data from three sites close to Hadrian's Wall. *The Holocene*, **4**(2), 165–173.

Dumayne-Peaty, L., 1998. Human impact on the environment during the Iron Age and Romano-British times: Palynological evidence from three sites near the Antonine Wall, Great Britain. *Journal of Archaeological Science*, **25**(3), 203–214.

Durand, S. R., Shelley, P. H., Antweiler, R. C., and Taylor, H. E., 1999. Trees, chemistry, and prehistory in the American Southwest. *Journal of Archaeological Science*, **26**(2), 185–203.

Eckstein, D., 1969. *Entwicklung und Anwendung der Dendrochronologie zur Alterbestimmung der Siedlung Haithabu*. Ph.D. dissertation, Hamburg University, Hamburg.

Eckstein, D., and Wrobel, S., 2007. Dendrochronological proof of origin of historic timber – retrospect and perspectives. Proceedings of the symposium on tree rings in archaeology, climatology and ecology, April 20–22, 2006 in Tervuren, Belgium. *Schriften des Forschungszentrums Jülich, Reihe Umwelt/Environment*, **74**, 8–20.

Eckstein, D., Wazny, T., Bauch, J., and Klein, P., 1986. New evidence for the dating of Netherlandish paintings. *Nature*, **320**(6061), 465–466.

Eckstein, J., Leuschner, H. H., Giesecke, T., Shumilovskikh, L., and Bauerochse, A., 2010. Dendroecological investigations at Venner Moor (northwest Germany) document climate-driven woodland dynamics and mire development in the period 2450–2050 BC. *The Holocene*, **20**(2), 231–244.

English Heritage, 1998. *Dendrochronology: Guidelines on Producing and Interpreting Dendrochronological Dates*. Peterborough: English Heritage. http://www.english-heritage.org.uk/publications/dendrochronology-guidelines/

English Heritage, 2010. *Waterlogged Wood: Guidelines on the Recording, Sampling, Conservation and Curation of Waterlogged Wood*, 3rd edn. Peterborough: English Heritage. http://www.english-heritage.org.uk/publications/waterlogged-wood/

Esper, J., Frank, D., Büntgen, U., Verstege, A., Hantemirov, R. M., and Kirdyanov, A. V., 2009. Trends and uncertainties in Siberian indicators of 20th century warming. *Global Change Biology*, **16**(1), 386–398.

Fantucci, R., 2007. Dendrogeomorphological analysis of shore erosion along Bolsena lake (Central Italy). *Dendrochronologia*, **24** (2–3), 69–78.

Ferguson, C. W., and Graybill, D. A., 1983. Dendrochronology of bristlecone pine; a progress report. *Radiocarbon*, **25**(2), 287–288.

Friedrich, M., Kromer, B., Hofmann, J., and Kaiser, K. F., 1998. Paleo-environment and radiocarbon calibration as derived from lateglacial/early Holocene tree-ring chronologies. *Quaternary International*, **61**(1), 27–39.

Friedrich, M., Kromer, B., Spurk, H., Hofmann, J., and Kaiser, K. F., 1999. Paleo-environment and radiocarbon calibration as derived from lateglacial/early Holocene tree-ring chronologies. *Quaternary International*, **61**(1), 27–39.

Fritts, H. C., 1976. *Tree Rings and Climate*. London: Academic.

Génova, M., Ballesteros-Cánovas, J. A., Díez-Herrero, A., and Martínez-Callejo, B., 2011. Historical floods and dendrochronological dating of a wooden deck in the Old Mint of Segovia, Spain. *Geoarchaeology*, **26**(5), 786–808.

Genries, A., Morin, X., Chauchard, S., and Carcaillet, C., 2009. The function of surface fires in the dynamics and structure of a formerly grazed old subalpine forest. *Journal of Ecology*, **97**(4), 728–741.

Grabner, M., Wimmer, R., and Weichenberger, J., 2004. Reconstructing the history of log-drifting in the Reichraminger Hintergebirge, Austria. *Dendrochronologia*, **21**(3), 131–137.

Grissino-Mayer, H. D., 2003. A manual and tutorial for the proper use of an increment borer. *Tree-Ring Research*, **59**(2), 63–79.

Grissino-Mayer, H. D., (2014). The science of tree rings (formerly, The Ultimate Tree-Ring Web Site); http://web.utk.edu/~grissino/

Guyette, R. P., Cutter, B. E., and Henderson, G. S., 1991. Long-term correlations between mining activity and levels of lead and cadmium in tree-rings of eastern red-cedar. *Journal of Environmental Quality*, **20**(1), 146–150.

Haglöf, 2014. How to use and take care of the Haglöf increment borer. http://www.haglofcg.com/index.php?option=com_docman&task=doc_view&gid=20&tmpl=component&format=raw&Itemid=100&lang=en

Haneca, K., Wazny, T., Van Acker, J., and Beeckman, H., 2005. Provenancing Baltic timber from art historical objects: success and limitations. *Journal of Archaeological Science*, **32**(2), 261–271.

Haneca, K., Čufar, K., and Beeckman, H., 2009. Oaks, tree-rings and wooden cultural heritage: a review of the main characteristics and applications of oak dendrochronology in Europe. *Journal of Archaeological Science*, **36**(1), 1–11.

Hantemirov, R. M., and Shiyatov, S. G., 2002. A continuous multimillennial ring-width chronology in Yamal, northwestern Siberia. *The Holocene*, **12**(6), 717–726.

Hayashida, F. M., 2005. Archaeology, ecological history, and conservation. *Annual Review of Anthropology*, **34**, 43–65.

Hillam, J., and Groves, C., 1996. Tree-ring research at Windsor Castle: aims and initial results. In Dean, J. S., Meko, D. M., and Swetnam, T. W. (eds.), *Tree Rings, Environment and Humanity: Proceedings of the International Conference, Tucson, Arizona, 17–21 May 1994*. Tucson: Radiocarbon, Department of Geosciences, University of Arizona, Tucson, pp. 515–523.

Hillam, J., Groves, C. M., Brown, D. M., Baillie, M. G. L., Coles, J. M., and Coles, B. J., 1990. Dendrochronology of the English Neolithic. *Antiquity*, **64**(243), 210–220.

Hoffsummer, P., 2002. *Les charpentes du XIe au XIXe siècle: Typologie et évolution en France du Nord et en Belgique*. Paris: Monum, Éditions du Patrimoine.

Hogg, A., Lowe, D. J., Palmer, J., Boswijk, G., and Bronk Ramsey, C., 2012. Revised calendar date for the Taupo eruption derived by ^{14}C wiggle-matching using a New Zealand kauri ^{14}C calibration data set. *The Holocene*, **22**(4), 439–449.

Holmes, R. L., 1983. Computer-assisted quality control in tree-ring dating and measurement. *Tree-Ring Bulletin*, **43**, 69–78.

Jacoby, G. C., Bunker, D. E., and Benson, B. E., 1997. Tree-ring evidence for an A.D. 1700 Cascadia earthquake in Washington and northern Oregon. *Geology*, **25**(11), 999–1002.

Jacoby, G. C., Workman, K. W., and D'Arrigo, R. D., 1999. Laki eruption of 1783, tree rings, and disaster for northwest Alaska Inuit. *Quaternary Science Reviews*, **18**(12), 1365–1371.

Jansma, E., van Lanen, R. J., Sturgeon, K., Mohlke, S., and Brewer, P. W., 2012. TRiDaBASE: a stand-alone database for storage, analysis and exchange of dendrochronological metadata. *Dendrochronologia*, **30**(3), 209–211.

Kaennel, M., and Schweingruber, F. H., 1995. *Multilingual Glossary of Dendrochronology: Terms and Definitions in English, German, French, Spanish, Italian, Portuguese and Russian*. Berne: Paul Haupt.

Kagawa, A., and Leavitt, S. W., 2010. Stable carbon isotopes of tree rings as a tool to pinpoint the geographic origin of timber. *Journal of Wood Science*, **56**(3), 175–183.

Kaiser, K. F., Friedrich, M., Miramont, C., Kromer, B., Sgier, M., Schaub, M., Boeren, I., Remmele, S., Talamo, S., Guibal, F., and Sivan, O., 2012. Challenging process to make the Lateglacial tree-ring chronologies from Europe absolute – an inventory. *Quaternary Science Reviews*, **36**, 78–90.

Kames, S., Tardif, J. C., and Bergeron, Y., 2011. Anomalous earlywood vessel lumen area in black ash (*Fraxinus nigra* Marsh.) tree rings as a potential indicator of forest fires. *Dendrochronologia*, **29**(2), 109–114.

Lageard, J. G. A., and Drew, I. B., 2008. Hydrogeomorphic control on tree growth responses in the Elton area of the Cheshire Saltfield, UK. *Geomorphology*, **95**(3–4), 158–171.

Lageard, J. G. A., and Ryan, P. A., 2013. Microscopic fungi as subfossil woodland indicators. *The Holocene*, **23**(7), 990–1001.

Lageard, J. G. A., Thomas, P. A., and Chambers, F. M., 2000. Using fire scars and growth release in subfossil Scots pine to reconstruct prehistoric fires. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **164**(1–4), 87–99.

Lageard, J. G. A., Howell, J. A., Rothwell, J. J., and Drew, I. B., 2008. The utility of *Pinus sylvestris* L. in dendrochemical investigations: pollution impact of lead mining and smelting in Darley Dale, Derbyshire, UK. *Environmental Pollution*, **153**(2), 284–294.

LaMarche, V. C., Jr., and Hirschboeck, K. K., 1984. Frost rings in trees as records of major volcanic eruptions. *Nature*, **307**(5947), 121–126.

Lewis, D., and Smith, D., 2004. Dendrochronological mass balance reconstruction, Strathcona Provincial Park, Vancouver Island, British Columbia, Canada. *Arctic, Antarctic, and Alpine Research*, **36**(4), 598–606.

Luckman, B. H., 1988. Dating the moraines and recession of Athabasca and Dome Glaciers, Alberta, Canada. *Arctic and Alpine Research*, **20**(1), 40–54.

Mann, M. E., Bradley, R. S., and Hughes, M. K., 1998. Global-scale temperature patterns and climate forcing over the past six centuries. *Nature*, **392**(6678), 779–787.

McCarroll, D., and Loader, N. J., 2004. Stable isotopes in tree rings. *Quaternary Science Reviews*, **23**(7–8), 771–801.

McCarroll, D., Pettigrew, E., Luckman, A., Guibal, F., and Edouard, J.-L., 2002. Blue reflectance provides a surrogate for latewood density of high-latitude pine tree rings. *Arctic, Antarctic, and Alpine Research*, **34**(4), 450–453.

Miles, D., 2006. Refinements in the interpretation of tree-ring dates for oak building timbers in England and Wales. *Vernacular Architecture*, **37**(1), 84–96.

Mills, C. M., and Crone, A., 2012. Dendrochronological evidence for Scotland's native timber resources over the last 1000 years. *Scottish Forestry*, **66**(1), 18–33.

Müllerová, J., Szabó, P., and Hédl, R., 2014. The rise and fall of traditional forest management in southern Moravia: a history of the past 700 years. *Forest Ecology and Management*, **331**, 104–115.

Munaut, A. V., 1966. Recherches dendrochronologiques sur *Pinus silvestris*: II. Première application des méthodes dendrochronologiques à l'étude de pins sylvestres sub-fossiles (Terneuzen, Pays-Bas). *Agricultura, 2e Serie*, **14**(3), 361–389.

Munro, M. A. R., 1983. An improved algorithm for cross-dating tree-ring series. *Tree-Ring Bulletin*, **44**, 17–27.

Nash, S. E., 1999. *Time, Trees, and Prehistory: Tree-Ring Dating and the Development of North American Archaeology, 1914–1950*. Salt Lake City: University of Utah Press.

Nayling, N., and Susperregi, J., 2014. Iberian dendrochronology and the Newport medieval ship. *International Journal of Nautical Archaeology*, **43**(2), 279–291.

Neuwirth, B., Schweingruber, F. H., and Winiger, M., 2007. Spatial patterns of central European pointer years from 1901 to 1971. *Dendrochronologia*, **24**(2–3), 79–89.

Nicolussi, K., and Patzelt, G., 1996. Reconstructing glacier history in Tyrol by means of tree-ring investigations. *Zeitschrift für Gletscherkunde und Glazialgeologie*, **32**, 207–215.

Nicolussi, K., Kaufmann, M., Patzelt, G., van der Plicht, J., and Thurner, A., 2005. Holocene tree-line variability in the Kauner Valley, Central Eastern Alps, indicated by dendrochronological analysis of living trees and subfossil logs. *Vegetation History and Archaeobotany*, **14**(3), 221–234.

Okochi, T., Hoshino, Y., Fujii, H., and Mitsutani, T., 2007. Nondestructive tree-ring measurements for Japanese oak and Japanese beech using micro-focus X-ray computed tomography. *Dendrochronologia*, **24**(2–3), 155–164.

Patrick, G. J., and Farmer, J. G., 2006. A stable lead isotopic investigation of the use of sycamore tree rings as a historical biomonitor of environmental lead contamination. *Science of the Total Environment*, **362**(1–3), 278–291.

Payette, S., and Delwaide, A., 1991. Variations séculaires du niveau d'eau dans le basin de la rivière Boniface (Québec nordique): Une analyse dendroécologique. *Géographie Physique et Quaternaire*, **45**(1), 59–67.

Payne, R. J., Edwards, K. J., and Blackford, J. J., 2013. Volcanic impacts on the Holocene vegetation history of Britain and Ireland? A review and meta-analysis of the pollen evidence. *Vegetation History and Archaeobotany*, **22**(2), 153–164.

Pelfini, M., Santilli, M., Leonelli, G., and Bozzoni, M., 2007. Investigating surface movements of debris-covered Miage Glacier, Western Italian Alps, using dendroglaciological analysis. *Journal of Glaciology*, **53**(180), 141–152.

Pilcher, J. R., Baillie, M. G. L., Schmidt, B., and Becker, B., 1984. A 7272-year tree-ring chronology for western Europe. *Nature*, **312**(5990), 150–152.

Pluskowski, A., Boas, A. J., and Gerrard, C., 2011. The ecology of crusading: investigating the environmental impact of the holy war and colonisation at the frontiers of medieval Europe. *Medieval Archaeology*, **55**, 192–225.

Regent Instruments, Inc., 2014. *WinDENDRO: An Image Analysis System for Tree-Rings Analysis*. http://www.regentinstruments.com/assets/windendro_about.html

Reynolds, A. C., Betancourt, J. L., Quade, J., Patchett, P. J., Dean, J. S., and Stein, J., 2005. $^{87}Sr/^{86}Sr$ sourcing of ponderosa pine used in Anasazi great house construction at Chaco Canyon, New Mexico. *Journal of Archaeological Science*, **32**(7), 1061–1075.

Richardson, D. M., 2000. *Ecology and Biogeography of Pinus*. Cambridge: Cambridge University Press.

Rinne, K. T., Loader, N. J., Switsur, V. R., and Waterhouse, J. S., 2013. 400-year May-August precipitation reconstruction for Southern England using oxygen isotopes in tree rings. *Quaternary Science Reviews*, **60**, 13–25.

Robertson, I., Froyd, C. A., Walsh, R. P. D., Newbery, D. M., Woodborne, S., and Ong, R. C., 2004. The dating of dipterocarp tree rings: establishing a record of carbon cycling and climatic change in the tropics. *Journal of Quaternary Science*, **19**(7), 657–664.

Rocky Mountain Tree-Ring Research, (2013). Oldlist – a database of ancient trees. http://www.rmtrr.org/oldlist.htm

Saas-Klaassen, U., 2002. Dendroarchaeology: successes in the past and challenges for the future. *Dendrochronologia*, **20**(1–2), 87–93.

Sass-Klaassen, U., Vernimmen, T., and Baittinger, C., 2008. Dendrochronological dating and provenancing of timber used as foundation piles under historic buildings in The Netherlands. *International Biodeterioration and Biodegradation*, **61**(1), 96–105.

Schöne, B. R., and Schweingruber, F. H., 2001. Dendrochronologische Untersuchungen zur Verwaldung der Alpen am Beispiel eines inneralpinen Trockentals (Ramosch, Unterengadin, Schweiz). *Botanica Helvetica*, **111**(2), 151–168.

Schulthess, J., 1990. *Der Einfluss von Entwässerung auf die Bewaldung eines Hochmoores: Eine Studie zur rezenten Bewaldungsentwicklung am Etang de la Gruère (JU)*. Diplomarbeit, Geographisches Institut Universität Zürich.

Schweingruber, F. H., 1983. *Tree Rings: Basics and Applications of Dendrochronology*, 1st edn. Dordrecht: D. Reidel.

Schweingruber, F. H., 1988. *Tree Rings: Basics and Applications of Dendrochronology*. Dordrecht: D. Reidel

Schweingruber, F. H., 1996. *Tree Rings and Environment Dendroecology*. Berne: Paul Haupt.

Schweingruber, F. H., Eckstein, D., Serre-Bachet, F., and Bräker, O. U., 1990. Identification, presentation and interpretation of event years and pointer years in dendrochronology. *Dendrochronologia*, **8**, 9–38.

Scuderi, L. A., 1993. A 2000-year tree-ring record of annual temperatures in the Sierra Nevada mountains. *Science*, **259**(5100), 1433–1436.

Sheppard, P. R., (2014). 'Try skeleton plotting for yourself!' An interactive Java-language application. Cross dating tree rings using skeleton plotting. http://www.ltrr.arizona.edu/skeletonplot/introcrossdate.htm.

Shroder, J. F., Jr., 1978. Dendrogeomorphological analysis of mass movement on Table Cliffs Plateau, Utah. *Quaternary Research*, **9**(2), 168–185.

Shumilov, O. I., Kasatkina, E. A., Lukina, N. V., Kirtsideli, I. Y., and Kanatjev, A. G., 2007. Paleoclimatic potential of the northernmost juniper trees in Europe. *Dendrochronologia*, **24**(2–3), 123–130.

Smiley, T. L., 1958. The geology and dating of Sunset Crater, Flagstaff, Arizona. In Anderson, R. Y., and Harshbarger, J. W. (eds.), *Guidebook of the Black Mesa Basin, Northeastern Arizona: Ninth Field Conference, October 16, 17, and 18, 1958*. Arizona: New Mexico Geological Society, pp. 186–190.

Smith, D. J., and Lewis, D., 2007. Dendroglaciology. In Elias, S. A. (ed.), *Encyclopedia of Quaternary Science*. Amsterdam: Elsevier, Vol. 2, pp. 986–994.

Smith, K. T., and Shortle, W. C., 1996. Tree biology and dendrochemistry. In Dean, J. S., Meko, D. M., and Swetnam, T. W. (eds.), *Tree Rings, Environment and Humanity: Proceedings of the International Conference, Tucson, Arizona, 17–21 May 1994*. Tucson: Radiocarbon, Department of Geosciences, University of Arizona, pp. 629–635.

Sorg, A., Bugmann, H., Bollschweiler, M., and Stoffel, M., 2010. Debris-flow activity along a torrent in the Swiss Alps: minimum frequency of events and implications for forest dynamics. *Dendrochronologia*, **28**(4), 215–223.

Speer, J. H., 2010. *Fundamentals of Tree-Ring Research*. Tucson: University of Arizona Press.

Stahle, D. W., Cook, E. R., Cleaveland, M. K., Therrell, M. D., Meko, D. M., Grissino-Mayer, H. D., Watson, E., and Luckman, B. H., 2000. Tree ring data document 16th century megadrought over North America. *EOS. Transactions of the American Geophysical Union*, **81**(12), 121–125.

Stoffel, M., Schneuwly, D., Bollschweiler, M., Lièvre, I., Delaloye, R., Myint, M., and Monbaron, M., 2005. Analyzing rockfall activity (1600–2002) in a protection forest – a case study using dendrogeomorphology. *Geomorphology*, **68**(3–4), 224–241.

Swetnam, T. W., and Baisan, C. H., 1996. Historical fire regime patterns in the southwestern United States since A.D. 1700. In Allen, C. D. (ed.), *Fire Effects on Southwestern Forests: Proceedings of the Second La Mesa Fire Symposium. Los Alamos, New Mexico, 29–31 March 1994*. USDA Forest Service General Technical Report RM-GTR-286. Fort Collins: US Department of Agriculture Forest Service, Rocky Mountain Forest and Range Experiment Station, pp. 11–32.

Swetnam, T. W., Allen, C. D., and Betancourt, J. L., 1999. Applied historical ecology: using the past to manage for the future. *Ecological Applications*, **9**(4), 1189–1206.

Thompson, M., 2008. *The White War: Life and Death on the Italian Front 1915–1919*. London: Faber and Faber.

Timberlake, S., and Prag, A. J. N. W. (eds.), 2005. *The Archaeology of Alderley Edge: Survey, Excavation and Experiment in an Ancient Mining Landscape*. Oxford: J. and E. Hedges. British Archaeological Reports, British Series 396.

Turney, C. S. M., Fifield, L. K., Hogg, A. G., Palmer, J. G., Hughen, K., Baillie, M. G. L., Galbraith, R., Ogden, J., Lorrey, A., Tims, S. G., and Jones, R. T., 2010. The potential of New Zealand kauri (*Agathis australis*) for testing the synchronicity of abrupt climate change during the last glacial interval (60,000–11,700 years ago). *Quaternary Science Reviews*, **29** (27–28), 3677–3682.

Tyers, I., 1999. *Dendro for Windows Program Guide*, 2nd edn. Archaeological Research and Consultancy at the University of Sheffield, ARCUS Report 500.

Tyers, I., 2012. Dendrochronological samples of structural timbers. In Arrowsmith, P., and Power, D. (eds.), *Roman Nantwich: A - Salt-Making Settlement: Excavations at Kingsley Fields 2002*. Oxford: Archaeopress. British Archaeological Reports, British Series 557, pp. 150–151.

VIAS, Vienna Institute of Archaeological Science, 2005. *Video Time Table. Installation and Instruction Manual*. Rev. 2.1. Vienna: VIAS

Vreugdenhil, S. J., Kramer, K., and Pelsma, T., 2006. Effects of flooding duration, -frequency and -depth on the presence of saplings of six woody species in north-west Europe. *Forest Ecology and Management*, **236**(1), 47–55.

Walker, M. J. C., 2005. *Quaternary Dating Methods*. Chichester: Wiley.

Watmough, S. A., 1999. Monitoring historical changes in soil and atmospheric trace metal levels by dendrochemical analysis. *Environmental Pollution*, **106**(3), 391–403.

Watmough, S. A., and Hutchinson, T. C., 2002. Historical changes in lead concentrations in tree-rings of sycamore, oak and Scots pine in north-west England. *Science of the Total Environment*, **293**(1V3), 85–96.

Wils, T. H. G., Sass-Klaassen, U. G. W., Eshetu, Z., Bräuning, A., Gebrekirstos, A., Couralet, C., Robertson, I., Touchan, R., Koprowski, M., Conway, D., Briffa, K. R., and Beeckman, H., 2011. Dendrochronology in the dry tropics: the Ethiopian case. *Trees*, **25**(3), 345–354.

Woodhouse, C. A., Pederson, G. T., and Gray, S. T., 2011. An 1800-yr record of decadal-scale hydroclimatic variability in the upper Arkansas River basin from bristlecone pine. *Quaternary Research*, **75**(3), 483–490.

Worbes, M., 2002. One hundred years of tree-ring research in the tropics – a brief history and an outlook to future challenges. *Dendrochronologia*, **20**(1–2), 217–231.

Wunder, J., Reineking, B., Hillgarter, F.-W., Bigler, C., and Bugmann, H., 2011. Long-term effects of increment coring on Norway spruce mortality. *Canadian Journal of Forest Research*, **41**(12), 2326–2336.

Yadav, R. R., 1992. Dendroindications of recent volcanic eruptions in Kamchatka, Russia. *Quaternary Research*, **38**(2), 260–264.

Yamaguchi, D. K., Hoblitt, R. P., and Lawrence, D. B., 1990. A new tree-ring date for the ‘floating island’ lava flow, Mount St. Helens, Washington. *Bulletin of Volcanology*, **52**(7), 545–550.

Yanosky, T. M., 1983. *Evidence of Floods on the Potomac River from Anatomical Abnormalities in the Wood of Flood-Plain Trees*. Washington, DC: US Government Printing Office. US Geological Survey Professional Paper 1296.

Zielinski, G. A., and Germani, M. S., 1998. New ice-core evidence challenges the 1620s BC age for the Santorini (Minoan) eruption. *Journal of Archaeological Science*, **25**(3), 279–289.

Zielonka, T., Holeksa, J., and Ciapała, S., 2008. A reconstruction of flood events using scarred trees in the Tatra Mountains, Poland. *Dendrochronologia*, **26**(3), 173–183.

Cross-references

Geographical Information Systems (GIS)
Geomorphology
Mass Movement
Paleoenvironmental Reconstruction
Radiocarbon Dating
Santorini
Volcanoes and People

DMANISI

C. Reid Ferring
Department of Geography, University of North Texas, Denton, TX, USA

Dmanisi is an Early Pleistocene hominin-bearing archaeological site located 65 km southwest of Tbilisi in the Republic of Georgia (41°20′10″N, 44°20′38″E; elevation: 910 m msl). Situated on a promontory at the confluence of the Masavera and Pinasaouri rivers, the site preserves up to 6.5 m of stratified ashfall and colluvial deposits conformably overlying the 1.85 Ma Masavera Basalt (Gabunia et al., 2000; Ferring et al., 2011). Dating by $^{40}Ar/^{39}Ar$ and paleomagnetism shows the site was occupied repeatedly from ca. 1.85 to 1.76 Ma, with rapid accumulation of hominin fossils during a brief interval ca. 1.77 Ma (Lordkipanidze et al., 2007; Messager et al., 2011).

Sediments are divided into nine major strata, separated by minor erosional surfaces; soils reveal periods of slow deposition and/or stability following episodes of ashfall or colluvial deposition. These deposits contain stratified occupation surfaces, with lithic artifacts and associated faunas. In the main excavation areas, extensive piping (shallow tunnellike features created by corrosion of the underlying deposits), pipe collapse, and gullying have led to rapid burial and superb preservation of both hominin fossils and thousands of large mammal bones. Over 40 taxa of Eurasian large mammals are dominated by cervids, bovids, and carnivores; some of these have cut marks and percussion blows indicating butchery (Lordkipanidze et al., 2007). Thousands of lithic artifacts of a Mode I (core-flake) industry are associated with the faunal remains (Mgeladze et al., 2011).

Dmanisi is the oldest archaeological site outside of Africa (and in the temperate zone), preserving the largest and most complete sample of hominin fossils in the Lower Pleistocene record. The rich archaeological and paleontological materials are being studied in concert with formation analyses to document patterns of site occupation, faunal exploitation, and lithic technology.

Bibliography

Ferring, R., Oms, O., Agusti, J., Berna, F., Nioradze, M., Shelia, T., Tappen, M., Vekua, A., Zhvania, D., and Lordkipanidze, D., 2011. Earliest human occupations at Dmanisi (Georgian Caucasus) dated to 1.85–1.78 Ma. *Proceedings of the National Academy of Sciences*, **108**(26), 10432–10436.

Gabunia, L., Vekua, A., Lordkipanidze, D., Swisher, C. C., III, Ferring, R., Justus, A., Nioradze, M., Tvalcrelidze, M., Anton, S. C., Bosinski, G., Jöris, O., de Lumley, M.-A., Majsuradze, G., and Mouskhelishvili, A., 2000. Earliest Pleistocene hominid cranial remains from Dmanisi, Republic of Georgia: taxonomy, geological setting, and age. *Science*, **288**(5468), 1019–1025.

Lordkipanidze, D., Jashashvili, T., Vekua, A., Ponce de León, M. S., Zollikofer, C. P. E., Rightmire, G. P., Pontzer, H., Ferring, R., Oms, O., Tappen, M., Bukhsianidze, M., Agusti, J., Kahlke, R., Kiladze, G., Martinez-Navarro, B., Mouskhelishvili, A., Nioradze, M., and Rook, L., 2007. Postcranial evidence from early *Homo* from Dmanisi, Georgia. *Nature*, **449**(7160), 305–310.

Messager, E., Nomade, S., Voinchet, P., Ferring, R., Mgeladze, A., Guillou, H., and Lordkipanidze, D., 2011. $^{40}Ar/^{39}Ar$ dating and phytolith analysis of the Early Pleistocene sequence of Kvemo-Orozmani (Republic of Georgia): chronological and palaeoecological implications for the hominin site of Dmanisi. *Quaternary Science Reviews*, **30**(21–22), 3099–3108.

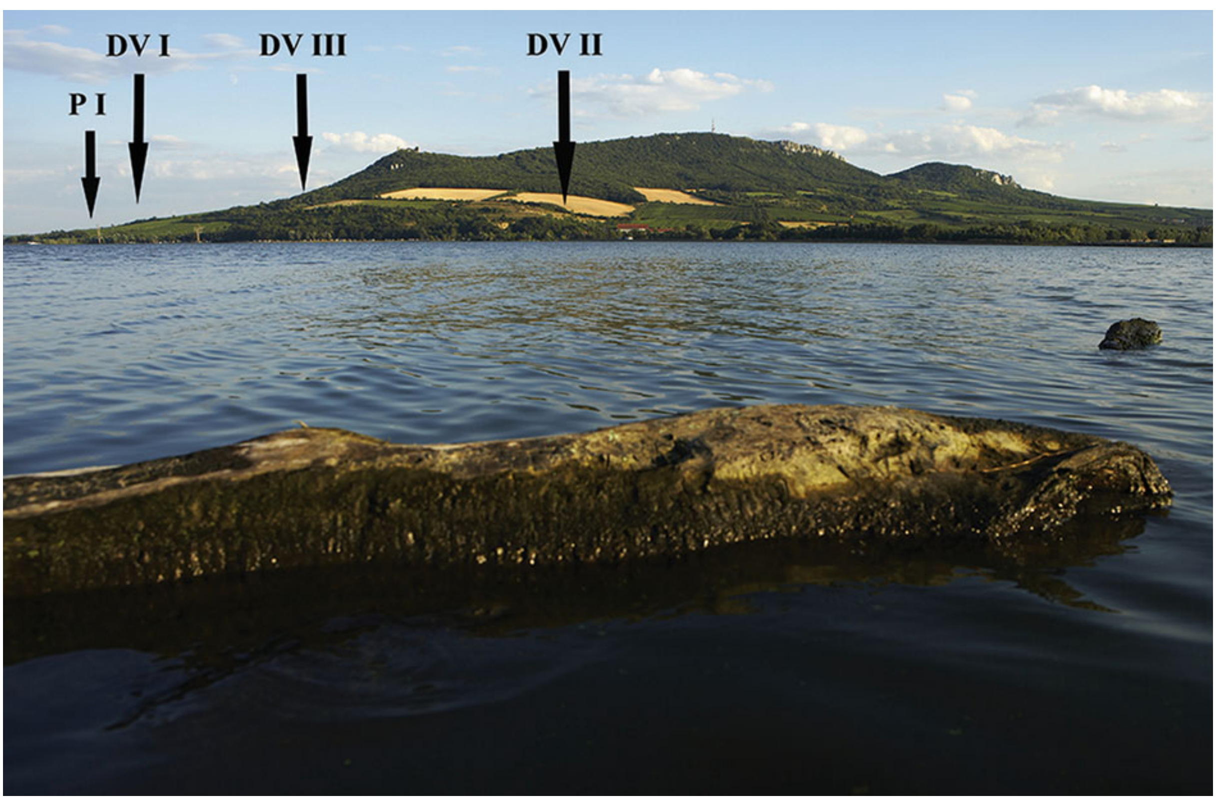
Mgeladze, A., Lordkipanidze, D., Moncel, M.-H., Despriee, J., Chagelishvili, R., Nioradze, M., and Nioradze, G., 2011. Hominin occupations at the Dmanisi site, Georgia, southern Caucasus: raw materials and technical behaviours of Europe's first hominins. *Journal of Human Evolution*, **60**(5), 571–596.

DOLNÍ VĚSTONICE, PAVLOV, MILOVICE

Jiří Svoboda
Insitute of Archaeology, Academy of Sciences of the Czech Republic, Dolní Věstonice, Czech Republic
Department of Anthropology, Faculty of Science, Masaryk University, Brno, Czech Republic

Introduction

These locations form a cluster of Gravettian (Pavlovian) sites on the northeastern slopes of the Pavlov Hills



Dolní Věstonice, Pavlov, Milovice, Figure 1 The Pavlovské Hills with sites of the Dolní Věstonice-Pavlov-Milovice area.

(550 m a.s.l.) in southern Moravia, Czech Republic. As a whole, the sites create an almost regular chain about 7 km long at elevations above 200 m a.s.l., which allowed an overview of the Dyje River Valley lying 30–40 m lower. The individual sites have been excavated since 1924 by Absolon (site DV I), Bohmers (DV I), Klíma (DV I–III, Pavlov I–III), Oliva (Milovice I), Svoboda (DV I–II, Pavlov II–II and VI, Milovice IV), and other excavators (Figure 1).

Stratigraphy and dating

A complete stratigraphic sequence of the last climatic cycle recorded at site DV II (bricketerry section) includes paleosols of the Last Interglacial and Early Glacial at the base (OSL dated to 110–70 ka), followed by laminated sandy loess (MIS 4) and a brown soil complex (MIS 3) and covered by a thick body of laminated sandy loess (mostly of MIS 2). The Gravettian (Pavlovian) occupation layer, located at the stratigraphic boundary between the brown MIS 3 soil complex and the above loess, is characterized by the expansion of parkland steppe (majority of ^{14}C dates between 32 and 29 cal ka).

Archaeology

These sites display a hierarchy ranging from large semi-permanent settlements with complex hearths, domestic constructions, and evidence of various activities, creating extensive clusters or palimpsests (DV I or Pavlov I), to smaller sites of seasonal and episodic character. The subsistence system seems to have been complex and labor-intensive. Although discussions are ongoing about intentionality of mammoth hunting, this animal played a key role in the human economy, accompanied by smaller animals such as reindeer, hares, a variety of carnivores, birds, fish, and plants (evidence of ground plant tissues and starch grains). Extensive mammoth bone deposits were located either inside the settlements or separately, in the adjacent gullies or on the slopes. Sophisticated blade and microblade technologies were based on siliceous rocks imported from distances of hundreds of kilometers. A variable industry of bone, ivory, and antler served as weapons and domestic tools. These sites have world primacy in the production of the earliest known ceramic figurines, textile structures, and cordage (recorded as imprints on the surface of burnt clay pieces). Besides zoomorphic and anthropomorphic figurines modeled in clay, these sites also provided delicate carvings in ivory and a variety of items for bodily decoration.

Physical anthropology

The sites of DV I, DV II, and Pavlov I provided a sample of early modern human skeletons from ritual burials, including four adult males (DV 13,14, and 16, Pavlov 1), one female (DV 3), one sexually undetermined individual (DV 15), and a large number of human skeletal fragments and teeth dispersed within the cultural layers.

Bibliography

Klíma, B., 1963. *Dolní Věstonice*. Praha: Nakladatelství Československé akademie věd.

Svoboda, J. (ed.), 2005. *Pavlov I Southeast: A window into the Gravettian Lifestyles*. Brno: Academy of Sciences of the Czech Republic, Institute of Archaeology. Dolní Věstonice Studies 14.

Trinkaus, E., and Svoboda, J. (eds.), 2006. *Early Modern Human Evolution in Central Europe: The people of Dolní Věstonice and Pavlov*. New York: Oxford University Press. Dolní Věstonice Studies 12.

DUMPS AND LANDFILL

Joseph Schuldenrein
Geoarchaeology Research Associates, Yonkers, NY, USA

Synonyms

Areas of designated waste management; Designated discard or refuse zones (public or private); Managed sites for waste processing and/or surface construction

Definition

Landfills are designed and modified sites for recycling postconsumer waste. They are regulated depositories whose function is dictated by statutes. Regulation is concerned with issues of contamination and groundwater. Refuse must be buried. Landfills can also be considered structural features of the terrain as their design is aimed to level or reconfigure topography of a landform or landscape.

Dumps are unregulated loci for discard on a variety of scales. They may be open facilities initially and become landfills when regulatory mechanisms are imposed and implemented. Dumps are initially proposed as sites for refuse deposition, and they may be considered activity areas in an archaeological sense.

Since landfills are the products of relatively recent and large sediment redeposition (often with the use of heavy equipment), they are not commonly traced to historic-age activities thereby minimizing their archaeological significance. As discussed below, the scale and extent of the twentieth century and subsequent landscape development is of such magnitude that future archaeologists will necessarily examine landfill contents and processes of formation when reconstructing the functional landscapes of the modern era (now referred to as the "Anthropocene").

Introduction

The terms "dumps" and "landfills" connote elements of the landscape that are unnatural and, per the definitions above, they are dominated by sediments that may be contaminated, polluted, and otherwise infested with waste remains that should not be handled without prescribed protocols and protection. Contemporary archaeological practice in most countries prohibits excavation through landfills without formal protective measures. In a preponderance of cases, landfills represent bodies of sediment that may have to be penetrated or removed to gain access to pristine surfaces that potentially contain sites or artifact assemblages in "primary context" (locations of original use). Paradoxically, those ostensibly pristine surfaces can themselves be sheet middens, which are essentially ancient discard surfaces and, in places, localized "dumps." Methodological advances in the study of the dumps of antiquity are at the heuristic core of advances in archaeological site formation studies. Yet, archaeologists either deliberately or circumstantially avoid collecting data on what the pioneering scholar of cultural landfills, W. Rathje, called "the archaeology of us" (Rathje et al., 1992; Shanks et al., 2004). Archaeologists who work in historic periods are increasingly drawn to studying older dumps and landfills since they represent early phases of large-scale discard in the case of the earliest municipalities. In addition to documenting historic patterns of land use, dumps and landfills also inform on land management strategies applied by the predecessors of today's city planners. The development of zoning and building codes is directly linked to the use of space for accommodating the various activities attendant to urban life; the discard footprints and processing activities of waste staging areas explain changing urban layouts, infrastructure configurations, and the legalities governing the patterned growth of cities. It is ultimately short-sighted to evade studies of contemporary landfills especially since, in the United States and elsewhere, formally designated landfills are in excess of 50 years old and may qualify for assessments of integrity according to the statutes of Section 106 of the National Historic Preservation Act guidelines (King, 2013).

Geoarchaeological approaches have been widely utilized in urban archaeological studies because they explain changing stratigraphies beginning at the general unconformity between "natural" and "cultural" sequences and progressing through various phases of anthropogenic landscape modification. Landfills and dumps pose unique taxonomic problems stratigraphically, because they may defy the laws of geological stratigraphy, which are based on "superposition" and "strata identified by fossils" (Rowe, 1961). Harris (1989: 29) calls attention to potential conflicts in projecting archaeological sequencing on formal geological stratification. Theoretically, each (archaeological) level or stratum is dated to a time *after* the date of manufacture of the most recent artifact found in it. Not so in the case of dumps and landfills where, in many cases, episodic recycling and remobilization of artifact-enriched discard sediments may produce inverted stratigraphies, or completely jumbled collections, depending on the objectives of landscape reconfigurations and reclamation goals.

Decay of historic features, historic drainage technologies, historic surface recontouring, and geochemical enrichments to natural sediment complexes are only some of the problems geoarchaeologists are called upon to solve. Varied techniques are applied to reconstruct site formation chronologies and processes at urban sites with landfill complexes in which the dominant sediment type in upper horizons is generally referred to as "fill." The entire question of designating a sediment as "fill" may now be called into question insofar as both ancient and modern dumps and landfills must be considered both as access nodes to archaeological exploration, as well as features that preserve the record of ancient and contemporary discard strategies.

Emergence of dumps and landfills in the archaeological record

Humans have discarded debris since the earliest hominins populated the earth. It is arguable that the study of debris and refuse comprises the core of archaeology, generally, as the residua of human activity accounts for a preponderance of interpretations bearing on the earliest human lifeways. Paleolithic archaeology, for example, is concerned with the analysis of nonperishable refuse in the form of waste flakes produced during stone tool manufacture and perishable remains such as charred or burnt organic matter in hearths. Those features ultimately represent the discard of food processing activities. Subsequent periods (i.e., Neolithic and onward) register progressively larger scales of discard reflective of the growing magnitude of human activity as social, political, and economic organizations became expansive and extended across the landscape. Near Eastern tells and Archaic or later shell mounds (see Stein, 1992), to cite classic examples, represent successive stages of occupation that incorporate abundant waste remains (middens) that can be considered the largest and most diagnostic features of the human imprint on the landscape. With time, the signatures of such discard features became progressively larger, more complex, and multifaceted even as discrete disposal loci were exposed to the ravages of erosion and landscaping. In such cases original discard loci often lost their integrity over the course of post-site abandonment and, in many cases, reoccupation. The earlier complex societies (i.e., third millennium BCE) witnessed large-scale terrain resculpting because of changing land use strategies (i.e., herding, agriculture), and these are often manifest in collapsed debris from structural features intermixed with pockets of deliberate human discard (the latter may retain primary integrity). Episodic erosion was a dominant formation process as well. Accordingly, there is clear evidence of deliberate leveling as land use and utilization changed. In the case of Archaic shell mounds, stratified accumulations of discrete shell types provide the evidence for reconstructions of ancient subsistence patterns bearing on both paleoenvironmental conditions and deliberate subsistence strategies. Those features are functionally akin to dumps.

Thus, the study of these most ancient of dumps and landfills is central to the study of archaeology in a variety of settings, scales, and contexts.

Viewed in a developmental context, the emergence and proliferation of complex societies have been accompanied by increasingly broader and deeper "discard" footprints as urban centers expanded outward and grew in size and frequency across global landscapes. Neolithic villages in Europe and Asia eventually gave way to medieval cities, while urban-like complexes in Mesoamerica and South and North America witnessed more punctuated and sporadic growth in later prehistoric times before giving way to the Euro-American expansions in the seventeenth century. Discard features changed in size, shape, and function in response to all of these changes in human socialization, commerce, and administrative organization.

The role of landfills and dumps is of great importance and will continue to assume an immediate and compelling role in archaeological investigations as these features become more prominent structural and functional components of the twenty-first-century landscape. Moreover, these features are global, serving populations in First, Second, and Third World economies. Urban and "central places" – in the classic sense of Christaller (1933) – require the large-scale creation of features and even "networks" of disposal loci that are tied to municipal and even regional waste disposal facilities and practices. In the developed world, dumps and landfills are usually zoned and monitored with city planning agencies regulating their utility, safety, and longevity. In nineteenth-century New York City, for example, 30 feet of "fill" was deliberately laid down around the perimeters of Lower Manhattan to impede shoreline erosion and to allow economic life to proceed despite frequent flooding (Cantwell and Wall, 2001). Geoarchaeological studies in and around New York City have demonstrated that this fill served to seal in evidence of prehistoric landscapes (see Schuldenrein and Aiuvalasit, 2011). In many parts of the Third World, more intermittent regulation, both historically and in the present day, accounts for longer and sustained "upbuilding" of dumps and landfills so that generations of residents live on the pure discard of their predecessors, often irrespective of health and safety concerns. Archaeologically, the "fill" components tell a multifaceted story of urban growth, development, and decay, allowing social scientists to reconstruct patterned occupation of the city and its supporting network of ancillary sites and rural landscapes.

A rethinking of the role of landfills and dumps is necessitated by contemporary concerns in environmental archaeology and geology, which consider questions of sustainability both within the archaeological record and across broader, more pressing, contemporary contexts of dramatic ecological change (Butzer, 2011). The "discard" component of the urban landscape is both deep and increasingly expansive. The "depth" dimension requires geoarchaeologists to examine tight stratigraphic "windows," or narrow exposures, in the substrate where classic archaeological excavations would be obviated by active subsurface infrastructures (i.e., gas and sewage lines). Also, because urban excavations are mostly conducted within the framework of cultural resource management (CRM), investigations are constrained by the guidelines of particular contracted questions that define and confine the limits of archaeological exploration spatially.

The prominence of what may be called "dump and landfill archaeology" is magnified further by the recent push to recalibrate and redefine geological epochs in the wake of humanly induced climate change and impact on ecological systems. Many scientists are now accepting the designation *Anthropocene* as a formal geological epoch based on climatic and geomorphic changes that have been either initiated or catalyzed by large-scale human impacts (Ruddiman, 2003; Price et al., 2011; Zalasiewicz et al., 2011; Brown et al., 2013). Amid considerable debate, the start of this Anthropocene epoch has been variously dated to the age of the European Industrial Revolution (ca. AD 1850). Among the significant adaptive strategies attendant to that initial date, many consider land-use changes in agricultural practice, the proliferation of extractive activities (i.e., mining and industrial production), and the growth of the urban landscape to have imposed the greatest influences.

Under these criteria, the emergence of large-scale dump and landfill features marks a categorical change in the material culture landscape as well as in the archaeological indicators that inform about the changing functions of such prominent discard features across time and space. Time-stratigraphic criteria are still not uniformly accepted by professionals, and research into the dating, utility, and archaeological signatures of the Anthropocene remains an ongoing focus of academic investigation.

Distinguishing archaeological landfills and dumps: a geoarchaeological question

It is widely accepted that the archaeological record is one of the most informative barometers of change in the evolution of the human condition, and some propose that it is the single best indicator. It certainly provides the most tangible evidence in the form of the material cultural record. Patterns of waste discard, which are ubiquitous archaeologically for nearly all prehistoric and historic time frames, may therefore be viewed as one of the most reliable parameters in explaining such change (Rathje et al., 1992).

That said, many archaeologists nevertheless look for primary evidence of human behavior beneath the deep and complex caps of recent to subrecent discard matrices. The objective is to reach the intact, or in situ, remains left by human activity in the same locations where those behaviors were conducted, i.e., not yet introduced into the trajectory of purposeful discard and disposal. The primary kind of setting informs only about a specific episode of past human action as it can be tied directly to a principal site and/or time frame under investigation. In traditional archaeological parlance, in situ context remains the measure of site integrity and the baseline from which artifact associations retain meaning for interpretive purposes.

Such pristine in situ contexts tend to be preserved under variable thicknesses of deposits (also referred to as "fill caps") whose integrity, or internal structure, has been variably compromised either geomorphically by surface or near-surface processes or functionally by repeated remobilization. Mobilized sediment, moved and redeposited through numerous agencies, has been considered, until recently, contextually meaningless. In urban areas, for example, massive earthmoving equipment is typically employed to re-level surfaces in preparation for new development projects, such as residential or commercial quarters. Why would the "fill cap" be useful for landscape reconstruction? In exurban zones, where historic manufacturing and industrial areas are being reclaimed for revived urban infrastructures, contaminated, polluted, and toxic subsurfaces are paved over and treated with neutralizing chemicals in the interests of "green development" and urban renewal. In this case, the compromised sediment is not even available for analysis, which further compounds the futility of addressing its primary source and formation history. These "fill caps" are thus typically viewed as "sealants" to enclose the primary evidence of historic events and land use. In the case of the buried city, minimal to modest disturbance by burial and recontouring of overlying fill does not damage the primary evidence of infrastructure formerly associated with earlier city function. Polluted exurban locales will almost certainly preserve the evidence of earlier manufacturing and refining technologies, if only because these facilities cannot be removed, given the risk of toxicity. In both scenarios, the buried landscapes become eligible for listing on the National Register of Historic Places if they meet the criteria of uniqueness mandated by the National Historic Preservation Act of 1966 (King, 2013).

And yet, forward-thinking archaeologists are now considering formation processes of the "fill cap" to provide insights into the logistics of modern landscape development. There is no doubt that changing configurations of massive bodies of recycled sediment reflect efficient strategies for land reclamation and systematic land-use transformations. Staged, flexible, and deliberate engineering designs have been increasingly integrated into urban planning schemes especially in the modern age (twenty-first century) of sustainability and conservation. In addition to the term "fill caps," the sediments that have been mobilized to bury relict features and recontour the landscape are also now referred to as "debris" and "rubble" (more generic classifications for the separate dump and landfill definitions described above). In cases where sediments from geological sources clearly formed the primary matrix and/or bulk of artificially tainted cultural deposits, the "fill cap" includes a prefix, i.e., "artificial fill in estuarine matrix" (Stone et al., 2002). For public and professional archaeologists alike, these terms carry no sense of context, and the terms themselves have negative or neutral connotations archaeologically. In Europe, stratified archaeological sites in urban areas may be separated by intervals of sedimentation laid down over historic neighborhoods that are centuries or even millennia in age. That sediment, if predating the era of heavy equipment, may incorporate ostensibly heterogeneous admixtures of locally remobilized rubble from the Roman and Greek periods. In most cases, those deposits are demonstrably devoid of any integrity, but there are situations wherein wholesale redeposition of matrix results in at least semi-primary retention of archaeological context. An example is when homogeneous pottery sherds and brick fragments have been displaced locally and form a "fill pocket" that preserves evidence for a specific object's use and function or, on a larger scale, for house architecture. It is noteworthy that the longevity and range of Europe's material culture record within sealed urban contexts have resulted in archaeologists often overlooking displaced objects whose internal structure is only minimally disturbed even though there is no in situ primary provenience in a "fill context." A common explanation is that the exponential growth of urban centers over the past 600 years has created a sedimentary context, with consequent loss of provenience, in which the most available "filling material" is Byzantine-age rubbles that were widely mobilized to modify early urban tracts for lot leveling and building construction. The long history of urban development in Europe (and elsewhere in the Old World) is such that priorities must be assigned to those archaeological components and contexts deemed most worthy of greater study. An implicit assumption here is that compromised spatiotemporal settings fall on the lower end of the preferred research spectrum even if such features may inform on, for example, ancient landscaping technology (see Harris, 1989: 48). An example here is the selection of specific sediment fabric ("fill derived") to form the substrate for well-trafficked Byzantine roads. Design plans for landscaping of similar features, with a concomitant dependence on "fill" materials, have been documented as early as the Roman period (Parker, 1874), but it has been registered much more extensively for the post-Byzantine.

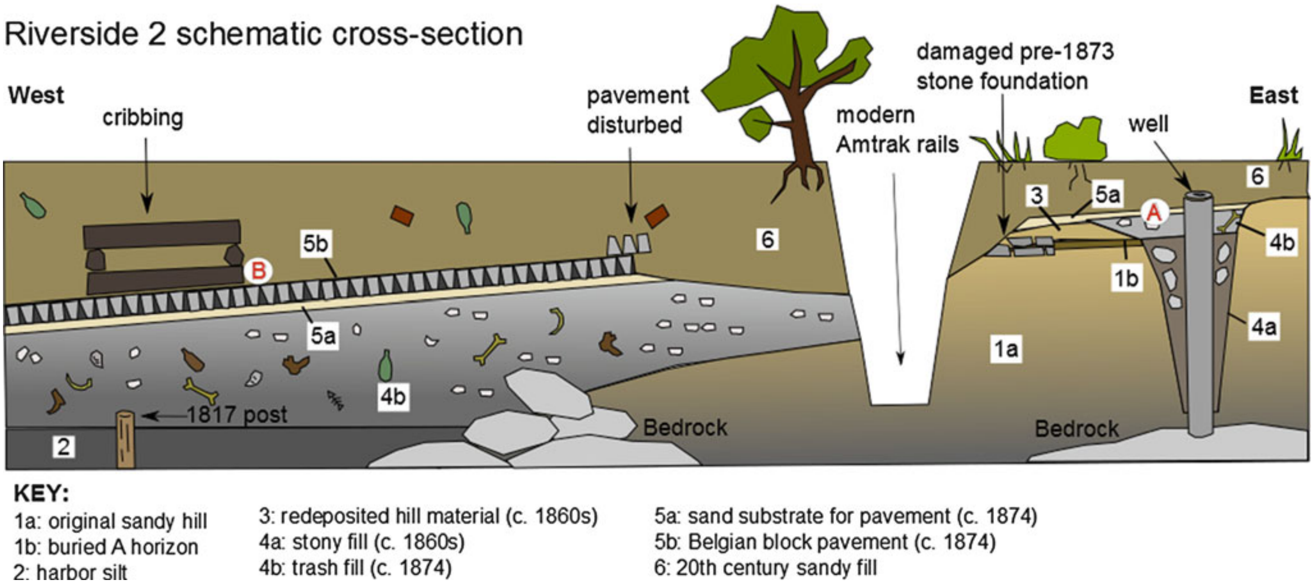
The situation is different in North America. The application of the "50-year rule" – the minimal wait time for designation to the National Register of Historic places, barring special eligibility circumstances (King, 2013) – coupled with the short duration (about 400 years) of the Euro-American occupation, and sparser population densities and settlement distributions, accounts for a scarcity of urban areas possessing deep archaeological successions. Multicomponent historic sites dating to the seventeenth and even early eighteenth century are comparatively rare. Patterns of urban redesign were also highly variable, given the diverse natural environments in the eastern, central, and western parts of the North American continent. Here, the disposition of "fill" across buried urban neighborhoods generates considerable interest and provides new information on site formation chronologies across time and in connection with changing historic settlement geography.

It can be argued, sensu lato, that today's fill is tomorrow's archaeological sediment because the former sediment bodies in fact reflect previous fill functions (i.e., relandscaping, recontouring). In many cases, their disposition, textural and compositional properties, and patterned redeposition may be associated with properties linked to the process of site burial and subsequent land use. For example, lime-rich sediment is often used to neutralize acidic and corrosive impacts in modern tank farms (oil depots). Accordingly, it is questionable as to whether or not those sediments should be designated as fill or more accurately "historic sediment." The former term is generic, implying undifferentiated and unsourced depositional complexes, while the latter is suggestive of primary, semi-primary, or displaced contexts linked to demonstrable functions and known periods. Given the growing acceptance of the Anthropocene concept and advances in site formation reconstructions (facilitated by high-technology applications), the latter designation of "historic sediment" should emerge as an umbrella for a nascent taxonomy centered on historic-age processes of site emergence, florescence, and abandonment. The use of the latter classificatory scheme would then restrict the term "fill" to situations wherein human engineering of the terrain produces artificially constructed or degraded landforms whose functions are mapped out in advance. That definition is more consistent with the growth of scientific methodologies, and it focuses on the dynamism of landscape archaeology and an overarching geoarchaeological perspective.

Stratigraphy and sedimentation at "landfill" sites: a case study from New York City

At complex archaeological sites, and specifically at urban centers preserving past and present architectural and landscape features (either humanly or naturally engineered), it is a challenging exercise to determine when a mappable sediment body is more appropriately classified a "fill" or an "occupational matrix." To distinguish these two deposits, a very loose identifying criterion would be whether or not the matrix was used to prepare and/or bury a former building to provide a new and currently usable lot or whether the deposit is a product of the degradation and collapse of nearby in situ locations and thus represents discrete human activities. As discussed earlier, there are gradations – for example, natural processes can embed and preserve re-transported anthropogenic components, and thus "occupational matrix" can be mobilized by natural forces eventually to create what appears to be fill. Generally, the modification of drainage grades by erosional processes is an indirect effect, but conversely, if a drainage landscape was explicitly designed to manage water flow, as in the canals of historic Dutch New York, that landform - component is legitimately categorized as an archaeological feature. The gradations between these two extremes are subtle, at the very least.

The subtleties of these distinctions are best demonstrated in a case study of a complex, stratified site on Manhattan's Upper West Side, which provides a semicontinuous, 4.5–5 m thick, record of human occupation from middle to later prehistoric times (6000–3000 BP) through the present (Figure 1) (Schuldenrein and Hulse, 2013). The schematic section illustrates the emergence of a complex landscape beginning with diagnostic sediments and soils of pre-Euro-American times. Strata 1a, 1b, and 2 register the pre-cultural ground surface of an elevated late glacial kettle moraine landscape (1a) sealed by a preserved (Holocene) soil (1b) and overlooking the postglacial estuary (2) of the Hudson River. The estuarine shoreline was utilized over the course of earlier Euro-American settlement. By the mid-nineteenth century, the natural landscape was impacted by initial urban settlement, originally activated by accelerated slope erosion (3) and subsequently by a growing population that constructed facilities, leveled land, and ultimately disposed of debris in several discrete locations, both locally (4a) and more extensively in designated waste discard locales (4b) (Figure 2a). The size and extent of the latter is a measure of the intensification of settlement and the emergence of ethnic neighborhoods. By the 1870s, a road network was designed that necessitated construction of a base with a pure sandy "fill" (in the formal sense of the term) to sustain a stable cobblestone roadway for horse and carriage and early automobile use (5b) (Figure 2a). The uppermost 2 m of the profile represents a complex of sediment bodies, poorly sorted and laterally and vertically variable in terms of sediment type and consistency (6). The construction of midtown Manhattan's twentieth-century (and now twenty-first) infrastructure is preserved within that complex of sediment. Isolated features were constructed within the matrices (e.g., a well, railroad tracks, and supporting railway station facilities); discrete features such as crib structures and paved segments were also found within that accumulation of sediment.



Dumps and Landfill, Figure 1 Schematic stratigraphy for Riverside 2 archaeological site, Manhattan, New York. Various historic landfilling units are labeled stratigraphically (marked 2 through 6) above the prehistoric strata (units 1a and 1b). Historic landfilling units date from Euro-American contact when the site marked the Dutch shoreline of early Manhattan Island (unit 2) through the twentieth-century "capping fill" (unit 6) which leveled off the contemporary site surface.

Dumps and Landfill, Figure 2 Discrete nineteenth-century landfilling units by type and age (see Figure 1 for location). (**a**) Excavation and landfilling activities associated with construction of a civil war era well (units 4a and 4b). (**b**) Preparations and construction of a cobblestone roadway, 1870s (units 5a and 5b).

Summarily, the "fill" designation can be applied to two functional deposit types: waste discard loci (Figures 1, 2: units 4a, 4b) attendant to mid-nineteenth-century neighborhood growth and an elevated base for a late nineteenth-century roadway (Figures 1, 2: units 5a, 5b). As the city expanded, both labor and heavy machinery were brought in to construct, deconstruct, and remake the infrastructure of the modern city. The multipurpose and remobilized sediment is essentially a third fill-type: collective residua whose sources are multiple. Those sediments and the feature elements found within it preserve a variable record of complex and penecontemporaneous activities over a century in the making. They include anthropogenic and displaced sediment contributions through erosional process.

Conclusion

Landfills and dumps are contemporary features of increasingly dense, complex, and human-engineered landscapes. They are critical archaeologically because contemporary research and cultural resource investigations often require that they be explored for subsurface structure if their footprints are slated for development. Since these landscapes are often polluted and toxic, noninvasive, and exploratory, high-technology strategies are often used to detect the archaeologically significant targets beneath them. Those strategies are often the venue for "beta-testing" of new methods designed to improve the yield of information. Landfills and dumps are also critical as artifacts and landscape archives themselves. They preserve a long history of industrial development that extends well into medieval times in Europe and Asia and over 300 years in North America. On a heuristic level, investigations of contemporary landscapes and dumps underscore one of the most pervasive themes of archaeological inquiry: the study of waste and discard. For earlier prehistory, that theme is all consuming, since the remains of human activity may represent the full extent of the archaeological record of the Paleolithic. With the passage of time, the archaeology of complex societies and cities is encapsulated, to a large degree, in the examination of discard facilities, which form key elements in infrastructure emergence and growth. The current debates over the legitimacy of a new geologic epoch, the Anthropocene, recast the significance of anthropogenic activities as measures of human impacts on the landscape. That thematic inquiry requires geoarchaeologists to develop new approaches to the study of "historic sediments." Those sediment bodies can no longer be generically dismissed as "fills" since sophisticated analytic and provenancing techniques allow for reconstructions of depositional origins and taphonomies. The ability to reconstruct and date site formation vectors and chronologies is an emerging tool in the interpretation of the human-engineered environment.

Bibliography

Brown, A. G., Tooth, S., Chiverrell, R. C., Rose, J., Thomas, D. S. G., Wainwright, J., Bullard, J. E., Thorndycraft, V. R., Aalto, R., and Downs, P., 2013. The Anthropocene: is there a geomorphological case? *Earth Surface Processes and Landforms*, **38**(4), 431–434.

Butzer, K. W., 2011. Geoarchaeology, climate change, sustainability: a Mediterranean perspective. In Brown, A. G., Bassell, L. S., and Butzer, K. W. (eds.), *Geoarchaeology, Climate Change, and Sustainability*. Boulder: Geological Society of America. GSA Special Paper 476, pp. 1–14.

Cantwell, A.-M. E., and Wall, D. Z., 2001. *Unearthing Gotham: The Archaeology of New York City*. New Haven: Yale University Press.

Christaller, W., 1933. *Die zentralen Orte in Süddeutchland: eine ökonomisch-geographische Untersuchung über die Gesetzmäßigkeit der Verbreitung und Entwicklung der Siedlungen mit städtischen Funktionen*. Jena: Fischer.

Harris, E. C., 1989. *Principles of Archaeological Stratigraphy*, 2nd edn. London: Academic.

King, T. F., 2013. *Cultural Resource Laws and Practice*, 4th edn. Lanham: AltaMira.

Parker, J. H., 1874. *The Archaeology of Rome*. Oxford: James Parker and Co., Vol. 1.

Price, S. J., Ford, J. R., Cooper, A. H., and Neal, C., 2011. Humans as major geological and geomorphological agents in the Anthropocene: the significance of artificial ground in Britain. *Philosophical Transactions of the Royal Society A*, **369**(1938), 1056–1084.

Rathje, W. L., Hughes, W. W., Wilson, D. C., Tani, M. K., Archer, G. H., Hunt, R. G., and Jones, T. W., 1992. The archaeology of contemporary landfills. *American Antiquity*, **57**(3), 437–447.

Rowe, J. H., 1961. Stratigraphy and seriation. *American Antiquity*, **26**(3), 324–333.

Ruddiman, W. F., 2003. The anthropogenic greenhouse era began thousands of years ago. *Climatic Change*, **61**(3), 261–293.

Schuldenrein, J., and Aiuvalasit, M., 2011. Urban archaeology and sustainability: a case study from New York City, USA. In Brown, A. G., Bassell, L. S., and Butzer, K. W. (eds.), *Geoarchaeology, Climate Change, and Sustainability*. Boulder: Geological Society of America. GSA Special Paper 476, pp. 153–172.

Schuldenrein, J., and Hulse, E., 2013. Landfills and site formation at a multi-component stratified archaeological site in the upper west site of Manhattan Island, NYC. Paper Presented at the Metropolitan Chapter of the New York State Archaeological Association.

Shanks, M., Platt, D., and Rathje, W. L., 2004. The perfume of garbage: modernity and the archaeological. *Modernism/Modernity*, **11**(1), 61–83.

Stein, J. K., 1992. *Deciphering a Shell Midden*. San Diego: Academic Press.

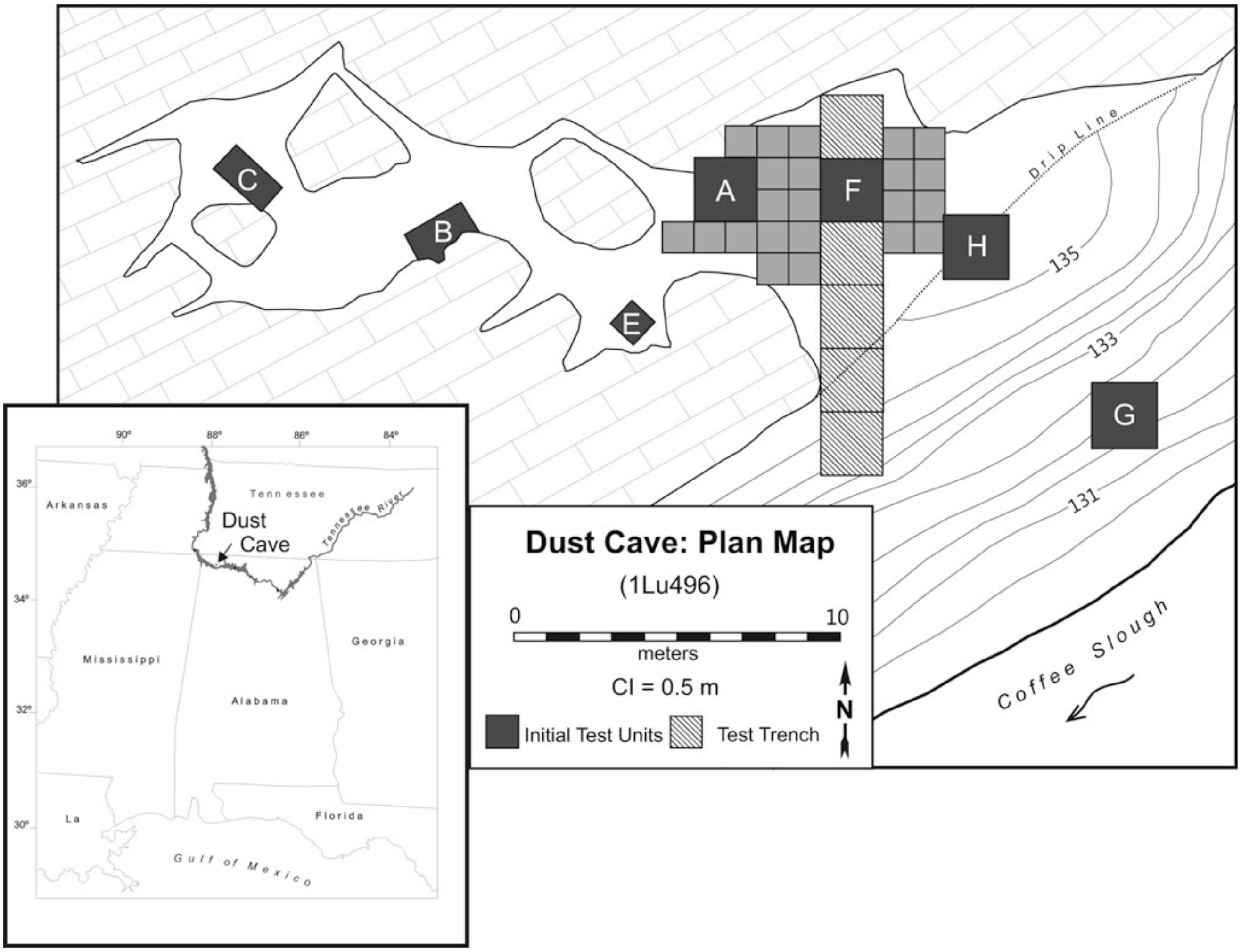
Stone, B. D., Stanford, S. D., and Witte, R. W., 2002. Surficial geological map of northern New Jersey. Miscellaneous Investigations Series Map I-2540-C. U.S. Geological Survey. Scale 1:100000.

Zalasiewicz, J., Williams, M., Fortey, R., Smith, A., Barry, T. L., Coe, A. L., Bown, P. R., Rawson, P. F., Gale, A., Gibbard, P., Gregory, F. J., Hounslow, M. W., Kerr, A. C., Pearson, P., Knox, R., Powell, J., Waters, C., Marshall, J., Oates, M., and Stone, P., 2011. Stratigraphy of the Anthropocene. *Philosophical Transactions of the Royal Society A*, **369**(1938), 1036–1055.

DUST CAVE, ALABAMA

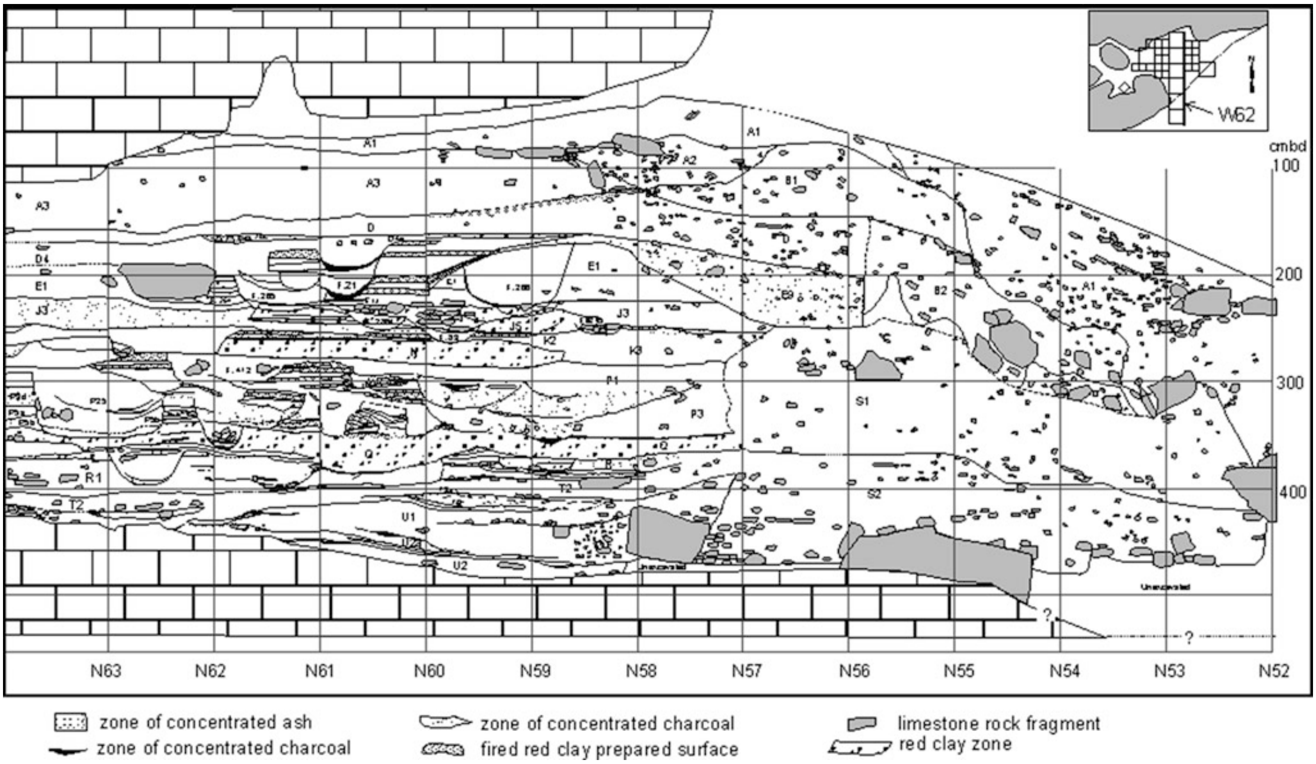
Sarah C. Sherwood
Environmental Studies, The University of the South, Sewanee, TN, USA

Dust Cave (1Lu492) is a habitation site located within a karstic vestibule in the middle Tennessee River Valley of northern Alabama (Figure 1). The cave entrance contains over 4 vertical meters of sediment generated through various processes (Figure 2), with human occupation



Dust Cave, Alabama, Figure 1 The location of Dust Cave and plan of the excavations.

being the primary source (Sherwood et al., 2004). This segment of the Tennessee River is generally considered a migration route and staging area for the colonization of eastern North America based primarily on the high concentration of fluted points found in the area (Anderson, 1996; Anderson and Sassaman, 1996; Anderson and Gillam, 2000; Anderson et al., 2010). Periodically occupied over 7,000 years, the cave contains well-preserved bone and botanical materials and exhibits microstratigraphy and intact occupation surfaces that provide insights into forager adaptations in the Midsouth from the end of the Pleistocene through the first half of the Holocene. The chronostratigraphic framework for Dust Cave is based on 43 ^{14}C dates, temporally diagnostic artifacts, and detailed geoarchaeological analysis that defines five cultural components designated: Quad/Beaver Lake/Dalton (10650–9200 cal BC), Early Side Notched (10000–9000 cal BC), Kirk Stemmed (8200–5800 cal BC), Eva/Morrow Mountain (6400–4000 cal BC), and Benton (4500–3600 cal BC) (Sherwood et al., 2004). Microstratigraphic and artifact analyses indicate that the primary differences in the deposits over time connect to the intensity of activity and spatial organization as it relates to changing conditions in the cave, not to the types of activities. Geomorphic transformations influenced the timing of the occupation at Dust Cave, especially the initial occupation in relation to the fluvial history of the Tennessee River at the Pleistocene/Holocene transition (Sherwood, 2009). This site is best known for the interdisciplinary research on subsistence (Walker et al., 2001; Hollenbach, 2007; Walker, 2007; Hollenbach, 2009; Hollenbach and Walker, 2010; Homsey et al., 2010; Carmody, 2012), and the geoarchaeological study of anthropogenic deposits within the cave (Sherwood et al., 2004; Sherwood and Chapman, 2005; Homsey and Capo, 2006; Sherwood, 2008; Homsey, 2010; Homsey and Sherwood, 2010).



Dust Cave, Alabama, Figure 2 Test trench stratigraphic profile (Modified from Sherwood et al., 2004).

Bibliography

Anderson, D. G., 1996. Models of Paleoindian and Early Archaic settlement in the lower Southeast. In Anderson, D. G., and Sassaman, K. E. (eds.), *The Paleoindian and Early Archaic Southeast*. Tuscaloosa: University of Alabama Press, pp. 29–57.

Anderson, D. G., and Gillam, J. C., 2000. Paleoindian colonization of the Americas: implications from an examination of physiography, demography, and artifact distribution. *American Antiquity*, **65**(1), 43–66.

Anderson, D. G., and Sassaman, K. E., 1996. Modeling Paleoindian and Early Archaic settlement in the Southeast: a historical perceptive. In Anderson, D. G., and Sassaman, K. E. (eds.), *The Paleoindian and Early Archaic Southeast*. Tuscaloosa: University of Alabama Press, pp. 16–28.

Anderson, D. G., Miller, D. S., Yerka, S. J., Gillam, J. C., Johanson, E. N., Anderson, D. T., Goodyear, A. C., and Smallwood, A. M., 2010. PIDBA (Paleoindian Database of the Americas) 2010: current status and findings. *Archaeology of Eastern North America*, **38**, 63–90.

Carmody, S. B., 2012. Middle archaic foraging adaptations in Northwest Alabama: a case study from dust cave, lauderdale county. *Alabama Journal of Alabama Archaeology*, **56**(2), 3–29.

Hollenbach, K. D., 2007. Gathering in the Late Paleoindian: Archaeobotanical remains from Dust Cave, Alabama. In Walker, R. B., and Driskell, B. N. (eds.), *Foragers of the Terminal Pleistocene in North America*. Lincoln: University of Nebraska Press, pp. 132–147.

Hollenbach, K. D., 2009. *Foraging in the Tennessee River Valley: 12,500 to 8,000 Years Ago*. Tuscaloosa: University of Alabama Press.

Hollenbach, K. D., and Walker, R. B., 2010. Documenting subsistence change during the Pleistocene/Holocene transition: investigations of paleoethnobotanical and zooarchaeological data from Dust Cave, Alabama. In VanDerwarker, A. M., and Peres, T. M. (eds.), *Integrating Zooarchaeology and Paleoethnobotany: A Consideration of Issues, Methods, and Cases*. New York: Springer, pp. 227–244.

Homsey, L. K., 2010. *The Hunter-Gatherer Use of Caves and Rockshelters in the American Midsouth: A Geoarchaeological and Spatial Analysis of Archaeological Features at Dust Cave*. Oxford: Archaeopress. British Archaeological Reports, International Series, Vol. 2129.

Homsey, L. K., and Capo, R. C., 2006. Integrating geochemistry and micromorphology to interpret feature use at Dust Cave, a Paleo-Indian through middle-archaic site in Northwest Alabama. *Geoarchaeology*, **21**(3), 237–269.

Homsey, L. K., and Sherwood, S. C., 2010. Interpretation of prepared clay surfaces at Dust Cave, Alabama: the role of actualistic studies. *Ethnoarchaeology Journal of Archaeological, Ethnographic, and Experimental Studies*, **2**(1), 73–98.

Homsey, L. K., Walker, R. B., and Hollenbach, K. D., 2010. What's for dinner? Investigating food-processing technologies at Dust Cave, Alabama. *Southeastern Archaeology*, **29**(1), 182–196.

Sherwood, S. C., 2008. Increasing the resolution of cave archaeology: micromorphology and the classification of burned deposits at Dust Cave. In Dye, D. (ed.), *Cave Archaeology in the Eastern Woodlands: Papers in Honor of Patty Jo Watson*. Knoxville: University of Tennessee Press, pp. 27–47.

Sherwood, S. C., 2009. The geoarchaeology of the Tennessee Valley: methodological and archaeological milestones. In Pritchard, E. (ed.), *Seventy Five Years of TVA Archaeology*. Knoxville: University of Tennessee Press, pp. 111–132.

Sherwood, S. C., and Chapman, J., 2005. The identification and potential significance of Early Holocene prepared clay surfaces: examples from Dust Cave and Icehouse Bottom. *Southeastern Archaeology*, **24**(1), 70–82.

Sherwood, S. C., Driskell, B. N., Randall, A. R., and Meeks, S. C., 2004. Chronology and stratigraphy at Dust Cave, Alabama. *American Antiquity*, **69**(3), 533–554.

Walker, R. B., 2007. Hunting in the Late Paleoindian period: faunal remains from Dust Cave, Alabama. In Driskell, B. N., and Walker, R. B. (eds.), *Foragers of the Terminal Pleistocene in North America*. Lincoln: University of Nebraska Press, pp. 99–115.

Walker, R. B., Detwiler, K. R., Meeks, S. C., and Driskell, B. N., 2001. Berries, bones and blades: reconstructing Late Paleoindian subsistence economies at Dust Cave, Alabama. *Midcontinental Journal of Archaeology*, **26**(2), 169–197.

E

EASTERN SAHARA: COMBINED PREHISTORIC EXPEDITION

Christopher L. Hill
Graduate College, Boise State University, Boise, ID, USA

Geoarchaeological studies conducted by the Combined Prehistoric Expedition (CPE) in the Eastern Sahara focused on stratigraphic sequences and paleolandscapes associated with Acheulian, Middle Paleolithic, Late Paleolithic, and Neolithic archaeological sites. Significant regions of study included Bir Sahara-Bir Tarfawi, Wadi Kubbaniya, and Nabta, all situated west of the Nile in southern Egypt. From its inception in 1962 until 1999, Fred Wendorf served as Director of the CPE, with Romuald Schild serving as Associate Director beginning in 1972 and as Director after 1999. After Schild's retirement in 2007 the CPE was led by Jacek Kabacinski. Schild was responsible for the geologic mapping and stratigraphic studies, although an impressive list of geologists and geoarchaeologists were members of, or collaborated with, the expedition.

The CPE first conducted research along the Nubian region of the Nile Valley as part of the construction of the Aswan High Dam (Wendorf, 1968). The study region extended from south of Aswan in Egypt to Wadi Halfa in Sudan, and it included Dungul Oasis and Kurkur Oasis. During the late 1960s, field studies were conducted primarily along the Nile Valley, but they included also the Western Desert's Fayum depression in 1969 (Wendorf and Schild, 1976). In 1972, the major focus of research became the Eastern Sahara (Wendorf and Schild, 1980).

Bir Sahara became a significant region for the CPE when, in 1971, Bahay Issawi discovered the stratigraphic exposures about 350 km south of Kharga (Schild and Wendorf, 1981). In 1972, spring vents west of Kharga at Balat (Dakhla) containing Acheulian bifaces were studied (Schild and Wendorf, 1977). Bir Sahara and nearby Bir Tarfawi were investigated in 1973 and 1974 and in three seasons from 1986 to 1988 (Wendorf et al., 1993). Although the Sahara-Tarfawi area contains some Neolithic scatters, the primary focus was on spring and pond deposits associated with Acheulian artifacts and a series of important Middle Paleolithic localities associated with either year-round lakes or playas. The Acheulian deposits may date to about 500,000 years ago, while the Middle Paleolithic localities range from before 200,000 to after 100,000 years ago. They reveal Middle and Late Pleistocene environments linked to fluctuating wetter and drier climates during the evolutionary transition to anatomically modern *Homo sapiens*.

The discovery of channel-like features in 1981 by space shuttle imaging radar (McCauley et al., 1982) prompted the CPE to conduct a systematic archaeological survey of the region south of Bir Tarfawi in 1984 (Wendorf et al., 1987). Hundreds of archaeological sites were found in the region of the radar channels. Most were assigned to the Neolithic, although several interesting Acheulian localities were also studied. Satellite images show a paleodrainage system extending from the highlands in southwestern Egypt towards the Bir Tarfawi region (Ghoneim and El-Baz, 2007), and it has also been suggested that water from the Nile flowed into the region during the Pleistocene (Maxwell et al., 2010).

A.S. Gilbert (ed.), *Encyclopedia of Geoarchaeology*, DOI 10.1007/978-1-4020-4409-0,

Wadi Kubbaniya, located in the region northwest of Aswan, revealed the presence of Late Paleolithic sites, discovered in a 1977 CPE survey. These sites were the subject of excavations in 1978 and from 1981 to 1984 (Close, 1989) and again in 2011–2012. The stratigraphic sequence at Kubbaniya shows the interplay between aggrading Nilotic alluvium and dunes and the presence of a lake, formed when the wadi was blocked by dunes from about 23,000 to 12,000 ^{14}C years BP. The stratigraphic sequence extends back to the Middle Paleolithic.

Nabta was discovered by the CPE in 1974. Neolithic sites from Nabta were studied in the 1970s, 1990s, and 2000s (Wendorf et al., 2001). The stratigraphy revealed a sequence of episodic climate changes dating from about 10,000 to 4,000 ^{14}C years BP. Wet episodes resulted in the formation of seasonal lakes, although at times small, permanent bodies of water may have persisted. An ecological argument has been put forward that the early bovid remains present at Nabta are domesticated cattle. During the late and final Neolithic, Nabta appears to have been a ceremonial center; pottery from this time is similar to that of the predynastic in the Nile Valley.

Bibliography

Close, A. E. (ed.), 1989. *The Prehistory of Wadi Kubbaniya*. Dallas: Southern Methodist University Press, Vols. 2 and 3.

Ghoneim, E., and El-Baz, F., 2007. The application of radar topographic data to mapping of a mega-paleodrainage in the Eastern Sahara. *Journal of Arid Environments*, **69**(4), 658–675.

Maxwell, T. A., Issawi, B., and Haynes, C. V., Jr., 2010. Evidence for Pleistocene lakes in the Tushka region, south Egypt. *Geology*, **38**(12), 1135–1138.

McCauley, J. F., Schaber, G. G., Breed, C. S., Grolier, M. J., Haynes, C. V., Issawi, B., Elachi, C., and Blom, R., 1982. Subsurface valleys and geoarchaeology of the Eastern Sahara revealed by shuttle radar. *Science*, **218**(4576), 1004–1020.

Schild, R., and Wendorf, F., 1977. *The Prehistory of Dakhla Oasis and Adjacent Desert*. Wrocław: Ossolineum.

Schild, R., and Wendorf, F., 1981. *The Prehistory of an Egyptian Oasis*. Wrocław: Ossolineum.

Wendorf, F. (ed.), 1968. *The Prehistory of Nubia*. Taos/Dallas: Fort Burgwin Research Center/Southern Methodist University Press.

Wendorf, F., and Schild, R., 1976. *Prehistory of the Nile Valley*. New York: Academic.

Wendorf, F., and Schild, R., 1980. *The Prehistory of the Eastern Sahara*. New York: Academic.

Wendorf, F., Close, A. E., and Schild, R., 1987. A survey of the Egyptian radar channels: an example of applied archaeology. *Journal of Field Archaeology*, **14**(1), 43–63.

Wendorf, F., Schild, R., Close, A. E., and Associates, 1993. *Egypt During the Last Interglacial: The Middle Paleolithic of Bir Tarfawi and Bir Sahara East*. New York: Plenum Press.

Wendorf, F., Schild, R., and Associates, 2001. *Holocene Settlement of the Egyptian Sahara volume 1. The Archaeology of Nabta Playa*. New York: Kluwer.

Cross-references

Gesher Benot Ya'aqov
Geomorphology
Paleoenvironmental Reconstruction

EL MIRÓN CAVE

Lawrence Guy Straus[1,2] and Manuel R. González Morales[2]
[1]Department of Anthropology, University of New Mexico, Albuquerque, NM, USA
[2]Instituto Internacional de Investigaciones Prehistóricas, Universidad de Cantabria, Santander, Spain

El Mirón is a large cave near Ramales de la Victoria in the Cantabrian Cordillera, roughly equidistant between the cities of Santander and Bilbao, about 20 km from the present shore at the mouth of the Asón River. Its coordinates are 43°14′48″ N × 3°27′5″ W × 260 m a.s.l. It is surrounded by mountains ≥1,000 m a.s.l. and, facing due west, dominates the upper valley of the Asón at a strategic crossroads of natural routes linking the Cantabrian coast with the Castilian *meseta* (N-S) and the Basque Country with Cantabria and Asturias (E-W). Discovered scientifically in 1903 by H. Alcalde del Río and L. Sierra, it was never systematically excavated until the present authors began their research in 1996 (e.g., Courty and Vallverdú, 2001; Straus et al., 2001; Cuenca-Bescós et al., 2009; González Morales and Straus, 2009; Straus et al., 2011; Straus and González Morales, 2012; Straus et al., 2014a; Straus et al., 2014b). The main excavations are in the spacious cave vestibule (30 m deep × 8–16 wide × 13 m high) and consist of two 9–10-m^2 blocks connected by a 9 × 1-m trench. The inner of the two blocks has a connected 3 × 1-m test pit excavated down from the base of a large crater dug by looters, plus a 4-m^2 area excavated to recover a Lower Magdalenian burial at the rear of the vestibule.

Sediments in the vestibule are of several sources; most are limestone debris from the cave ceiling and walls and colluvial silts and cobbles derived from the ancient alluvial infilling of the >100-m-long inner cave that had undergone numerous fill-and-cut episodes. There are also fine aeolian silt and organic materials derived from long-term occupations of the cave by humans, birds, and other animals. Sedimentology was done by the late William Farrand, micromorphology by Marie-Agnès Courty, and magnetic susceptibility by Brooks Ellwood. An aggregate total of ca. 5 m of deposit have been sampled by the excavations, but geophysical prospection shows a total depth of ca. 9 m to bedrock in the vestibule. The climatic and vegetational changes of the late Upper Pleistocene and early Holocene are documented by micromammalian remains, pollen, wood charcoal, seeds, and phytoliths studied, respectively, by Gloria Cuenca, Maria Jose Iriarte, Lydia Zapata, Leonor Peña, and Debora Zurro. The mammalian fauna from the post-Paleolithic and Magdalenian levels has been analyzed, respectively, by Jesús Altuna, Koro Mariezkurrena, and Manuel Pérez Ripoll and by Ana Belen Marín.

Eighty-four radiocarbon assays date the excavated layers between ca. 41,000 BP and AD 1400 (all dates uncal). Documented cultural occupations pertain to the late Mousterian, Gravettian, Solutrean, Initial, Lower, Middle, Upper, and Final Magdalenian, Azilian, Mesolithic, Neolithic, Chalcolithic, and Bronze Ages, with traces of Medieval visits, as well as modern use of the cave by both humans and livestock. There are significant depositional hiatuses in the early Holocene part of the sequence. The Mousterian, Gravettian, Azilian, and Mesolithic occupations are minor, but the other periods are represented by important residues of human utilization, from specialized hunting camps in the Solutrean (ca. 19,000–17,000) to major, long-term, complex, multifunctional residential base camps in the Lower Magdalenian (ca. 16,000–14,000 BP) to mini-village settlements with pit structures in the Neolithic (one of the oldest in northern Atlantic Spain at ca. 5800–4500 BP), Chalcolithic, and Bronze Age (ca. 4500–3200 BP), with abundant ceramic technology, wheat grains, domesticated ovicaprines, cattle, and pigs and, in the latter, evidence of metallurgy.

The Magdalenian sequence is one of the longest and most complete in Spain, and it shows continuity from the preceding Solutrean and into the succeeding Azilian. Pollen and micromammal evidence in particular point to cold, but more or less humid climatic conditions, with open landscapes dotted with pines and junipers during much of the Upper Paleolithic sequence, until the Late Glacial Interstadial, when woods began to recolonize the area. The Initial (17,000–16,000 BP) and Lower Magdalenian levels have numerous hearths with abundant fire-cracked rocks; masses of red deer (DNA analyzed by X. L. Hermoso-Buxán and Rhiannon Stevens) and ibex remains; salmon and other fish bones (DNA analyzed by Sonia Consuegra and Carlos García Leaniz); vast quantities of stone, antler, and bone tools and weapons; objects of personal adornment (perforated shells and teeth); and works of mobile art (notably a red deer stag scapula engraved with the image of a hind and a slate pendant engraved with the image of a horse). The Lower Magdalenian was the setting of the only human burial yet to be found in the Late Glacial of the Iberian Peninsula: an interment of a short, apparently healthy, middle-aged woman now represented by over half her bones,(but the cranium and most long bones were missing). The bones are stained with red ocher and deposited in sediments also stained with red ocher and sparkling with hematite crystals. The remains are currently under study by a team led by J. M. Carretero, and whose mtDNA and nDNA are being analyzed by a team led by S. Pääbo. The corpse, which (once skeletonized) was slightly disturbed by a carnivore, had been placed within a narrow space between a large fallen block and the rear vestibule wall, partly atop the bedrock ledge and partly in a pit dug into a preexisting Magdalenian level upon which the block had fallen. Subsequent to its fall, the block was engraved in late Lower-Middle Magdalenian times on its outward-oriented (west) surface and painted red on its inward-facing side (east). The rear vestibule wall is also covered with fine engravings, mainly lines, but also one horse and a possible bison.

Bibliography

Courty, M.-A., and Vallverdú, J., 2001. The microstratigraphic record of abrupt climate changes in cave sediments of the Western Mediterranean. *Geoarchaeology*, **16**(5), 467–499.

Cuenca-Bescós, G., Straus, L. G., González Morales, M. R., and García, J. C., 2009. The reconstruction of past environments through small mammals: from the Mousterian to the Bronze Age in El Mirón Cave (Cantabria, Spain). *Journal of Archaeological Science*, **36**(4), 947–955.

González Morales, M. R., and Straus, L. G., 2009. Extraordinary early Magdalenian finds from El mirón cave, Cantabria (Spain). *Antiquity*, **83**(320), 267–281.

Straus, L. G., and González Morales, M. R., 2012. *El Mirón Cave, Cantabrian Spain: The Site and its Holocene Archaeological Record*. Albuquerque: University of New Mexico Press.

Straus, L. G., González Morales, M. R., Farrand, W. R., and Hubbard, W. J., 2001. Sedimentological and stratigraphic observations in El Mirón, a late quaternary cave site in the Cantabrian Cordillera, northern Spain. *Geoarchaeology*, **16**(5), 603–630.

Straus, L. G., González Morales, M. R., and Carretero, J. M., 2011. Lower Magdalenian secondary human burial in El Mirón Cave, Cantabria, Spain. *Antiquity*, **85**(330), 1151–1164.

Straus, L. G., González Morales, M. R., Marín, A. B., and Iriarte, M. J., 2014a. The human occupations of El Mirón Cave (Ramales de la Victoria, Cantabria, Spain) during the Last Glacial Maximum/Solutrean period. *Espacio, Tiempo y Forma, Serie I, Nueva Epoca, Prehistoria y Arqueología*, **5**, 413–426.

Straus, L. G., González Morales, M. R., and Fontes, L. M., 2014b. Initial Magdalenian artifact assemblages in El Mirón Cave (Ramales de la Victoria, Cantabria, Spain): a preliminary report. *Zephyrus*, **73**, 45–65.

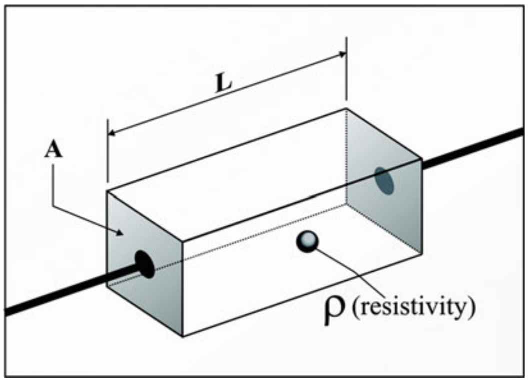
Straus, L.G., Gonzalez Morales, M. R., and Carretero, J. M., eds., 2015. The Red Lady of El Miron Cave: Lower Magdalenian Human Burial in Cantabrian Spain. Special issue of *Journal of Archaeological Science*.

ELECTRICAL RESISTIVITY AND ELECTROMAGNETISM

Alain Tabbagh
Université Pierre et Marie Curie, Paris, France

Introduction

Resistivity and electromagnetic prospecting are two methods by which the electrical resistivity of the ground can be measured. This property of resistivity quantifies the difficulty experienced by electrical currents in passing through the soil. As an example, most stones resist the flow of an electrical current. Clay is the opposite, and current readily flows through it. By using these geophysical methods, one attempts to describe the three-dimensional structure of the ground (Clark, 1996) without the intrusiveness and destruction of an excavation. Such information can be useful in evaluating the buried archaeological remains of a site. The quality of such information is



Electrical Resistivity and Electromagnetism, Figure 1 Definition of the resistivity of a prismatic body.

limited, however, first by the physical principle of the methods and second by the chosen spatial sampling interval. Nevertheless, one of these methods can probably be successful at a greater variety of sites than any other geophysical technique.

The ideas and procedures of resistivity surveys will be described first. The lesser known and more complex procedures of electrostatic and electromagnetic surveys will be discussed later. All of these very different techniques allow the measurement of the same parameter, the electrical resistivity of the soil. While the many different procedures may seem unusual, there are also many different types of magnetometers and several different types of ground-penetrating radars. Each has advantages.

Electrical resistivity

Electrical resistivity is indicated with the symbol ρ and is quantified with a unit called the ohm · meter ($\Omega \cdot$ m). If a resistance of R (in ohms) is measured between the ends of the rectangular prism shown in Figure 1, the resistivity of the medium contained within the prism will be $\rho = R\frac{A}{L}$, where A is the area of the cross-section of the medium, and L is the distance that electricity must cross along the length of the prism. For convenience, one may also talk about the conductivity (indicated by the symbol σ) of the medium, which is simply the reciprocal of resistivity: $\sigma = 1/\rho$.

In natural, earthen materials, this property of resistivity exhibits a broad range of variation (a wide dynamic range) from less than 1 $\Omega \cdot$ m to more than 10,000 $\Omega \cdot$ m. In soils and rocks, ions are the moving electric charges. Depending upon their location within the three phases of the subsurface medium (solids, liquids, and gases), these mobile ions fall into two categories: (1) ions dissolved in pore water that generate *volume conductivity* and (2) counter ions that can slide at the surface of clay platelets and generate *surface conductivity.* Counter ions are positively charged cations that adsorb onto the generally negatively charged surfaces of clay platelets, and thus, interpretation of conductivity/resistivity values becomes a matter of distinguishing between materials that contain clay and those that do not contain clay.

Materials without clay

Here, one observes a direct proportionality between the bulk resistivity, ρ_b, and the resistivity of the pore-filling water, ρ_w. The ratio between them, $F = \frac{\rho_b}{\rho_w}$, is called the formation factor. Consequently, one may assume that both solid and gas fractions can be considered in isolation and that all the electrical current circulates only through the pore water. For moist, porous soils, F can be as low as 4, while for stones, it can reach 100. If the porosity were to be constituted solely by a bundle of straight channels filled with water, F would be inversely proportional to the porosity, φ. In reality, however, the channels are not straight but tortuous because of the irregularity of structure and packing within the ground subsurface, and their sections as well as the length along their path may vary. Experiments conducted with saturated media have led to the formulation of Archie's law, which states: $F = \varphi^{-m}$, where φ is the porosity and the parameter m is not far from 2. In unsaturated media, this law behaves differently: $F = \theta^{-m}$, where θ is the volume water content.

Materials with clay

In fine-grained materials, volume conductivity is present, but surface conductivity also exists. The relationship that corresponds best with experiments is the simple addition of these two types of conductivity:

$$\sigma = \sigma_v + \sigma_s,$$

where σ_s is the surface conductivity and σ_v is the volume conductivity. However, except in areas of saline soils, surface conductivity plays the major role; a conductive soil must be interpreted as one containing a significant clay component, while a resistive soil is usually one with lower clay content. For all soils, an increase in water content will correspond to an increase in conductivity.

Consequences for archaeological prospection

The significance of these two different processes of electrical charge transport for archaeological prospection is twofold: (1) resistivity informs about the character of the natural substrate in which the archaeological remains are buried, and (2) one can assess the contrast that exists between a given archaeological feature and its surrounding medium depending upon their respective clay content. For instance, a ditch infilled with superficial soil of 70 $\Omega \cdot$ m resistivity that was originally dug into 30 $\Omega \cdot$ m loess will be imaged as a resistive feature, while the same infilled ditch dug into alluvial gravel of 300 $\Omega \cdot$ m resistivity will be imaged as a conductive feature.

It should be noted that the resistivity of sedimentary rocks may vary due to the influence of their clay fraction; even a wall built using solid limestone blocks can have a moderate resistivity of 100 $\Omega \cdot$ m if it contains several percent of clay, while another, clay-free, limestone may

Electrical Resistivity and Electromagnetism, Table 1 Electrical resistivity of layers that can be encountered in archaeological sites.

Subsurface medium	$\Omega \cdot$ m
Superficial clayey layer	15
Loess	30
Typical cultivated layer	70
Chalk	100
Sand, moist	200
Limestone	100–2,000
Sand (dry)	3,000
Crystalline stone	5,000

have a much higher resistivity of 2,000 $\Omega \cdot$ m. Some reference values and a few general rules of thumb are as follows. (1) The resistivity of water varies linearly with salt content from 0.25 $\Omega \cdot$ m for seawater to 20 or 100 $\Omega \cdot$ m for soft waters (containing little dissolved mineral content). (2) Clays in superficial formations show a narrow range of resistivity from 5 to 15 $\Omega \cdot$ m. (3) Sedimentary rocks exhibit a wide range in resistivity, from 20 $\Omega \cdot$ m for marl to 5,000 $\Omega \cdot$ m for sandstones. (4) Unweathered crystalline rocks and permafrost are both very resistive. (5) Generally, stones or fired bricks from building remains are more resistive than their surroundings, while earthen features, pits, pit-house fills, and ditches are more conductive. (6) In alluvial contexts, the sign of the contrasts can change abruptly when passing from gravel or sand to clay. Table 1 summarizes the order of magnitude in resistivity for different materials commonly encountered in an archaeological context.

Physical principles underlying the different techniques

The discussion of electrical current flowing though resistors (or soils) has so far assumed that these are steady currents that do not change with time. If, however, these are alternating currents, the applications become more complex, but also more valuable. The increased complexity occurs because two additional properties of soils can now affect the measurements. The first property is the *magnetic susceptibility* (κ) of the soil, a dimensionless constant; iron-containing minerals in the soil have the greatest effect on its magnetic susceptibility. The second property of soils is the *dielectric permittivity* (ε), measured in farads per meter (F/m); while this term is less familiar, this property controls the velocity of a radar pulse in the soil. Fortunately, the applications become more informative when these two additional properties of soils are measured, for they allow greater distinctions to be made between different soils and archaeological features.

Ground-penetrating radars work at a higher frequency; their operation is controlled by the conductivity (σ, which is the reciprocal of resistivity, ρ) and the dielectric permittivity of the soil. If the frequency is lower than 30 kHz, the dielectric property of the soil has little effect on measurements, leaving the other two properties, conductivity and susceptibility. Most electromagnetic (EM) instruments operate at this lower range of frequencies, and they can measure both the conductivity and the susceptibility of the soil, independently, with a single instrument.

These EM instruments will be described in greater detail later, but an important aspect will be introduced here. Many of them operate by sending an oscillating magnetic field from one coil of wire (the transmitter) through the soil to another coil (the receiver). This magnetic field is increasingly attenuated, the deeper it descends into the earth. However, a greater depth is possible if the soil is resistive or if the frequency of oscillation is lower. If the magnetic field is able to penetrate deeply into the soil (deep relative to the spacing between the two coils), then the EM instrument can follow the low induction number (LIN) approximation. This LIN approximation means that the coupling of the magnetic field from the transmitter to the receiver coil is directly proportional to the conductivity of the soil. These instruments are often called conductivity meters, and they are widely used in archaeology.

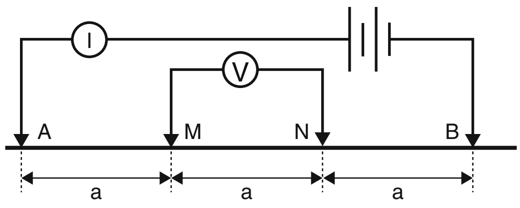
Direct current electrical prospecting (static approximation case)

To inject an electrical current into the soil, two electrodes (e.g., two metal stakes) are enough. It is impossible, however, to deduce the resistivity of the soil from the voltage difference between these two stakes and from the delivered current intensity. One can obtain only the sum of the two earth resistances at each stake. Fortunately, the voltage at locations other than the injection points is dependent on soil resistivity, and thus arrays of four electrodes – two electrodes for current injection and two others for the measurement of voltage differences – represent an effective solution for resistivity determination. Direct current (DC) electrical prospecting is achieved by using a quadrupole, which is often called "the resistivity method."

If one considers a homogeneous half-space of resistivity, ρ, and a direct current, $+I$, is injected with an electrode at a point A on its surface, the current density will be isotropically distributed (equal in all directions) and is expressed at a distance r from A by: $i_r = \frac{1}{2\pi r^2}$. By applying Ohm's law, the electric field is expressed by: $E_r = \frac{\rho I}{2\pi r^2}$, and the electrical potential by $V = \frac{\rho I}{2\pi r}$ (if the potential is 0 at infinity). If one considers a second electrode at a point B on the same surface, where the injected current emerges and is $-I$, it becomes possible to determine the voltage difference between two other electrodes serving as measurement points, M and N, yielding the following:

$$V_M - V_N = \Delta V = \frac{\rho I}{2\pi}\left[\frac{1}{MA} - \frac{1}{MB} - \frac{1}{NA} + \frac{1}{NB}\right],$$

where AM is the distance between electrodes A and M, BN is the distance between electrodes B and N, etc.

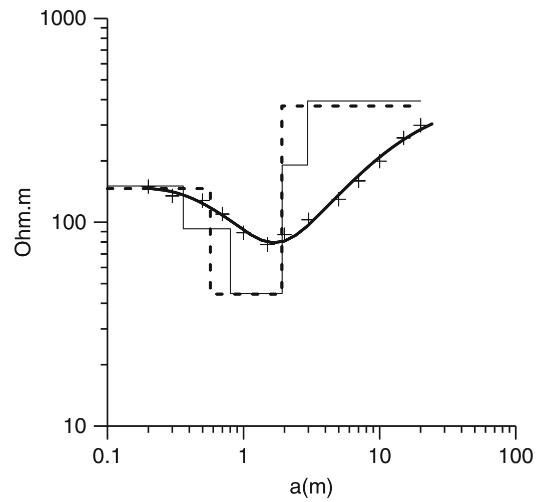


Electrical Resistivity and Electromagnetism, Figure 2 Schematic diagram of the Wenner α array.

The measurement of $\Delta V/I$ is proportional to ρ but also depends on the geometry of the four-electrode array, that is, on how the electrodes are arranged spatially. The apparent resistivity concept can express the measurement with one parameter, and it also compares the results obtained with different array geometries. The apparent resistivity, ρ_a, is the resistivity of a homogeneous ground that would give the same value of $\Delta V/I$ as the array that was used. It is thus expressed by using a geometrical coefficient K (in meters): $K = \frac{2\pi}{\frac{1}{AM} - \frac{1}{BM} - \frac{1}{AN} + \frac{1}{BN}}$ and $\rho_a = \frac{\Delta V}{I} K$. The apparent resistivity can be considered as a sort of global average value of the electrical resistivity of the soil volume that influences the measurement.

There exist an infinite number of ways to deploy the four electrodes over a ground surface, and therefore, some arbitrary procedures have been adopted that are advantageous from either a practical point of view, a theoretical one, or both. The first is the Schlumberger array where the four electrodes are placed along a straight line in a symmetrical disposition with MN ≪ AB; here $K = \frac{\pi AB^2}{4MN}$. For this array, all electrodes lie along the same line, but the inner ones that measure voltage (M and N) are separated by a much shorter distance than that separating them from the outer current electrodes (A and B). In the Wenner array, presented in Figure 2, the four electrodes are aligned but separated by the same distance, a, so that $K = 2\pi a$ for the A,M,N,B configuration (called Wenner α). Additionally, the electrode arrangement can be modified to yield $K = 6\pi a$ for the A,B,N,M configuration (called Wenner β, or Wenner dipole-dipole) and $K = 3\pi a$ for the A,M,B,N configuration (called Wenner γ). The electrodes can also be located at the four corners of a square, in which case $K = 10.72a$, where a is the side of the square. This holds true if electrodes A and B are adjacent; if they are located at the diagonally opposite corners of the square, then $K = 0$.

In the process of surveying, the electrodes are moved in order to measure a different spot in one's area of investigation or probe deeper into the subsurface. It is possible to limit the number of electrodes that must be moved for each voltage measurement by fixing one of them, for example, B, at a great distance (infinity), so that $K = 4\pi a$ if the three others stay aligned and separated by a. This array is called "pole-dipole." One voltage electrode and

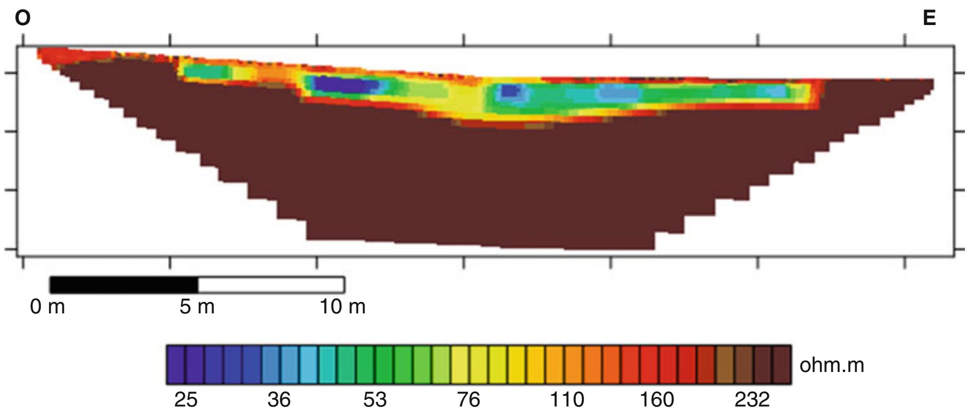


Electrical Resistivity and Electromagnetism, Figure 3 An example of a VES using the Wenner α configuration (in which the a spacing is gradually increased to deepen the sounding progressively. A log-log display is used to show the apparent resistivity measurements (+). A calculated curve (*black continuous line*) is the same for two different models of stratification, one with three layers (*dotted line*) and the other with five layers (*continuous thin line*), giving the same level of fitness between experimental and theoretical values. The thicknesses of the layers can be read on the horizontal axis and the resistivities on the vertical axis. For both scenarios, the dip in the curve reveals the conductive layer of clay at a depth of about 1 m.

one injection electrode can also be fixed at great distances from the moving electrodes to obtain the so-called pole-pole configuration where $K = 2\pi a$; here, only two electrodes are moved.

Historically, the resistivity method allows one to explore both the vertical and lateral distribution of resistivity. Vertical changes in resistivity (at one location) are revealed by increasing the electrode separation and sending the current deeper into the ground; lateral variations (at a constant depth) are detected by moving a quadrupole that has a fixed geometry around a wide area. The first type has been called "electrical sounding" (or vertical electrical sounding, VES). The second type has been called "resistivity profiling." In archaeological prospecting, one always makes a series of parallel profiles to get a map of apparent resistivity variations across a ground surface (see Figures 5 and 6). Both types of resistivity survey require an understanding of the effective depth of a measurement, as it is determined by the resistivity stratification of the soil and the electrode separation. As an approximation, the depth of investigation, that is, the soil thickness averaged by a measurement, is generally somewhat smaller than the smallest distance between one current-injection electrode and the closest voltage electrode.

As an example of the information provided by a VES, Figure 3 shows the result of an electrical sounding



Electrical Resistivity and Electromagnetism, Figure 4 Example of electrical resistivity tomography done at the archaeological site of La Citerne (Grand, Vosges, France). It shows a section perpendicular to a linear drainage depression cut into the underlying limestone; the drain was about 20 m wide and up to 1.2 m deep (Courtesy of C. Brinon). The drain is filled with conductive sediments, and the resistive limestone is underneath (Brinon, 2012, 146).

performed with a Wenner α configuration. The measurement was located where the soil contained planar strata and where, between a resistive limestone base and the moderately resistive topsoil, there was a conductive clayey layer resulting from the weathering of the limestone. Unfortunately, infinitely many different resistivity stratifications within the soil could yield the measurements that were obtained; there is no one-to-one relationship between a resulting curve and a specific sequence of strata. Two of the possible solutions are drawn in Figure 3, one with three layers (dotted line), the other with five (continuous thin line). Even though these solutions differ, both reveal the presence of the conductive layer of clay, and its approximate depth of around one meter is readily established on the horizontal axis of the graph.

It has been also recognized that both sounding and profiling can be combined by using multipole arrays, whether one opts for a mobile process wherein electrodes are moved or an immobile one (a stationary switched array). The two-dimensional (2D) switched array is also called "electrical resistivity tomography," or ERT. It allows a simultaneous measurement of resistivity variations in both the horizontal and the vertical dimension, generating what is called a resistivity pseudosection. It is achieved by placing a long line of n equidistant electrodes separated by the same distance, a. One first chooses the normal quadrupole configuration, for example, the Wenner array. The first measurement is made using electrodes 1, 2, 3, and 4; one then switches to electrodes 2, 3, 4, and 5 and repeats this operation down the line of electrodes until electrode n is reached. In this way, a first profile corresponding to the a-spacing is performed, generating a resistivity cross section at a uniform depth. Additional, deeper profiles are then produced by using electrodes 1, 3, 5, and 7, followed by switching to electrodes 2, 4, 6, and 8 and so on; this will yield a second profiling that reaches to a depth of approximately 2a due to the 2a spacing. All the possible successive spacings are then done the same way to a maximum spacing of (n–3)a. 2D interpretation transforms the pseudosection into vertical sections of resistivity variations. This 2D exploration process can be expanded into a 3D one by using a grid of electrodes that extend in two horizontal directions. An example of an interpretation of a 2D ERT is shown in Figure 4; this resistivity section reveals a low resistivity stratum caused by soil-filled drains above limestone bedrock.

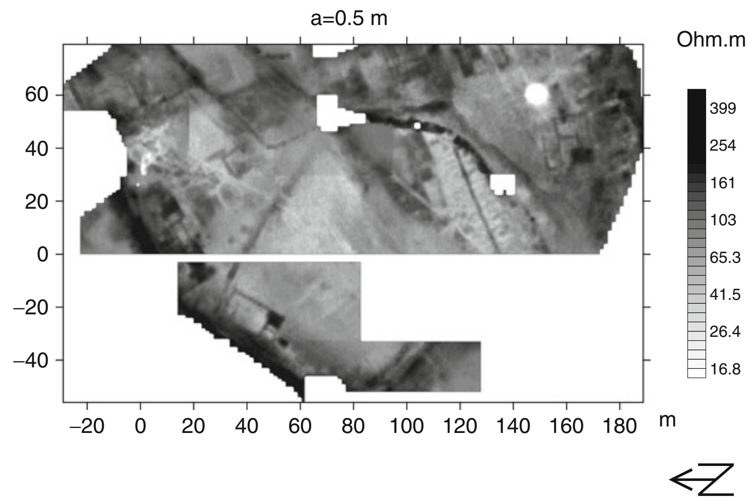
A substantial amount of equipment is needed to measure a pseudosection, and the survey is quite slow because of the greater number of electrodes that must be inserted into the soil before beginning to record measurements. A simplification for purposes of archaeological prospection has involved the development of moving multielectrode systems. Two different types, one hand held, and one mechanically towed, are described next.

Handheld devices

The best compromise between lightweight equipment and high data quality led to the adoption of the pole-pole array; several different depths can be explored by using moving in-line arrays of electrodes fixed to a rigid frame (Gaffney and Gater, 2003). With the RM15 from Geoscan Research Ltd., a set of four electrodes separated by 50 cm allows the sequential determination of a number of pole-pole measurements for each setting of the electrode array: three at a spacing of 0.5 m, two measurements with electrodes spaced by 1 m, and one measurement with a spacing of 1.5 m. Figure 5 is a resistivity map that was prepared with this procedure inside the small town of Grand (Vosges, France), an area of over 2 ha was mapped, and a series of gardens were revealed.

Mechanically towed systems

The device above is suitable for the survey of limited-size parcels, but for larger areas, this type of survey is still



Electrical Resistivity and Electromagnetism, Figure 5 An apparent resistivity map measured at 'le Pré Laguerre' (Grand, Vosges, France) using a pole-pole array with an electrode spacing of 0.5 m. Measurements were ended at the edges of the garden. The apparent resistivity was found to decrease as the depth of investigation increased due to the presence of a conductive substratum. The Gallo-Roman features are clearer on this shallow (a = 0.5 m) map, which proves that their depth is limited (Brinon, 2012, 224).

Electrical Resistivity and Electromagnetism, Figure 6 An automatic resistivity profiling (ARP©) instrument with a differential GPS positioning antenna, that is towed by a light, all-terrain vehicle (courtesy of Geocarta SA). The current is injected at poles A and B, while the voltages are measured at the three pairs of electrodes M and N.

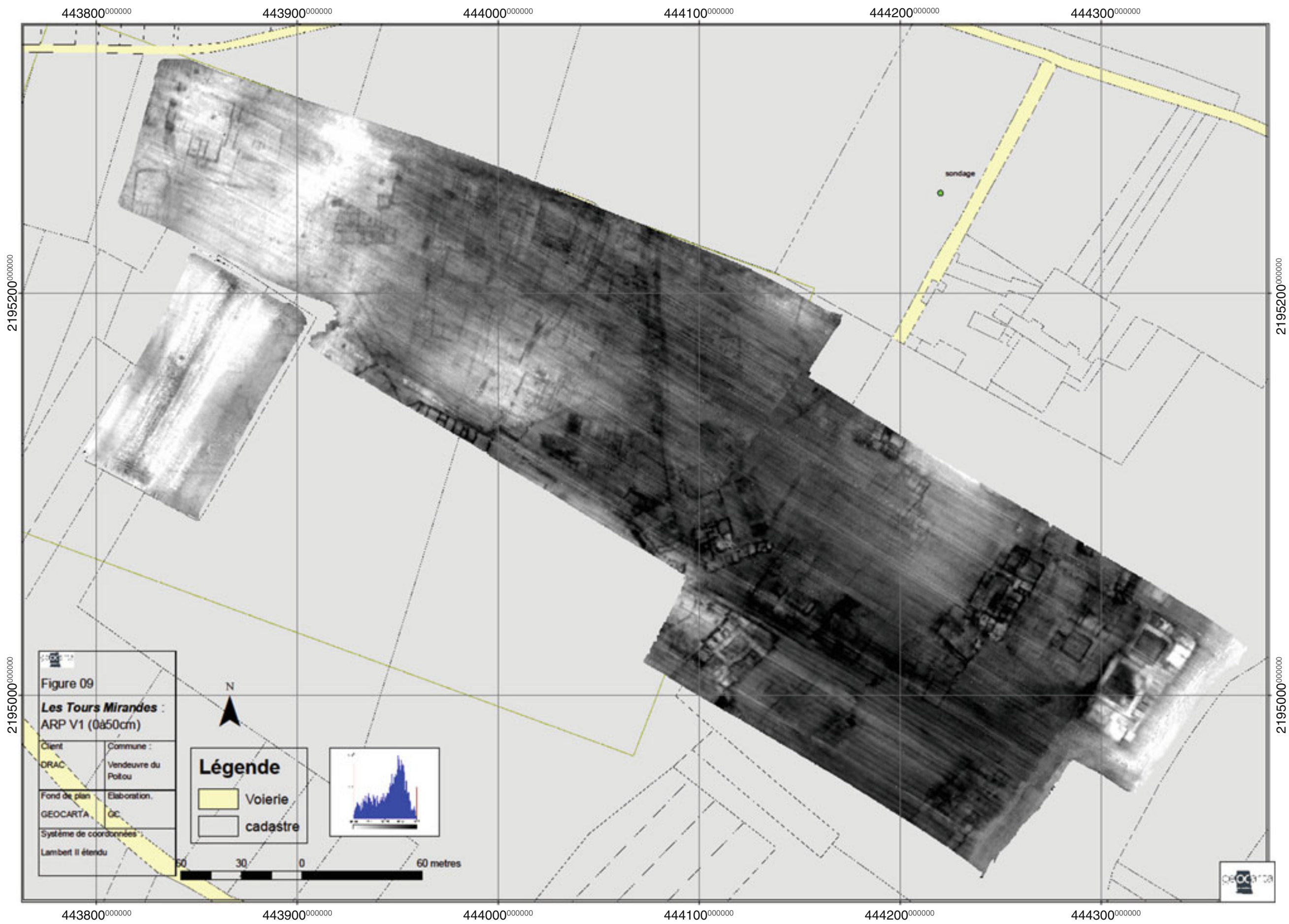
tedious and slow, and therefore expensive. For more extensive surveys, mechanically towed systems should be considered (Campana and Piro, 2009).

For such systems, two main problems need to be overcome: the measurement speed must be fast, and the electrical contact between each electrode and the soil must be good. Stable measurements of resistivity can be made in a few microseconds; therefore, resistivity meters have been designed to overcome the first limitation. The second problem is more difficult; the most effective solution has been to use heavy spiked wheels (weighing about 20 kg). A good instrument for archaeological prospection (Panissod et al., 1998) is a multipole system with one pair of current-injection wheels and three different pairs of voltage-measuring wheels, as illustrated in Figure 6. This is called a MUCEP (Multi-pole Continuous Electrical Profiling) or an ARP© (Automatic Resistivity Profiling) instrument. Simultaneous measurements can be taken with several depths of investigation afforded by the differently spaced voltage electrodes (Brinon et al., 2012).

The example shown in Figure 7 is a resistivity map of a 4-ha area at Tours Mirandes (Vendeuvre du Poitou, Vienne, France) from Caraire et al. (2011). Roads and stone foundations are revealed in this map; the resistivity of the surrounding soil varied from 15 Ω·m (clayey soils) to 120 Ω·m (at limestone outcrops).

Electrostatic prospecting

The DC electrical method has a major weakness in that it requires a good galvanic contact between the electrodes and the ground. This is not too difficult on cultivated soil in temperate climates, but it can be very difficult in arid areas and impossible on tarmacs and other hard layers.



Electrical Resistivity and Electromagnetism, Figure 7 An apparent resistivity map with a depth of investigation of 1 m that was measured at the Gallo-Roman city of Tours Mirandes (Vendeuvre du Poitou, Vienne, France). This map is superimposed onto a historical property map (Courtesy of Geocarta and Johan Durand, HERMA, Poitiers University).

In such challenging situations, one can generate an electric field by applying electrostatic charges and then measuring voltage differences in the air, and not in the ground itself. If an electric charge is located in the air just above the ground, and both low frequency and *LIN* assumptions are valid, then the electric potential at another point can be approximated by the same formula that is applied to DC prospection: $V = \frac{\rho I}{2\pi r}$. Thus, the electrostatic method is a generalization of the DC electrical one, where the source of the electric field is a pair of electrical charges, $+Q$ and $-Q$, that constitute an open capacitor. It can be called a "capacity-coupled resistivity method" or "capacitive resistivity method." This method has the same capabilities as the DC electrical resistivity method, and it can be used for both vertical and lateral investigations with simple quadrupole or multipole arrays. The required assumptions can be met, for typical values of soil resistivity, by using a frequency between 3 and 300 kHz and by limiting the depth of exploration to at most 10–20 m, which is suitable for archaeological prospection. The advantages that result from the absence of galvanic contacts are important: (1) one can survey over insulating surfaces and also delicate surfaces, for example, painted walls, and (2) it is easy to move a quadrupole (or a multipole) continuously over a surface without significant changes in the impedance of the poles (Panissod et al., 1998; Souffaché et al., 2010).

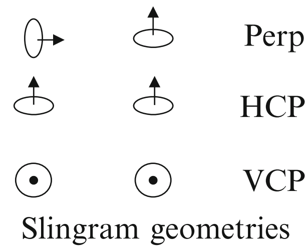
Electromagnetic prospecting, Slingram EMI

Another way of avoiding electrical contact with the soil is with the application of a time-varying magnetic field. In a conductive medium, this time variation causes eddy currents to flow, which in turn generate secondary magnetic fields that can be measured with receiving coils. Several different sources for the primary magnetic field can be applied: one can use low-frequency radio broadcasting transmitters, the magnetic field from large or small loops or coils, or a long wire lying on the ground surface. For archaeological prospection, a suitable combination of the correct depths of investigation and good lateral resolution is achieved with instruments that have a pair of small coils. One is a transmitting coil that emits a continuous monofrequency magnetic field, and the other, or companion, receiving coil measures, the resulting secondary magnetic field. The suitability of this instrument was recognized after a series of test studies begun in the mid-1960s (Scollar et al., 1990). The coils may have orientations that differ from each other; it is also possible to use several receivers or transmitters, but the distances, L, between the coils should not significantly exceed the lateral and vertical size of the features that are sought. This type of instrument has several names; the name slingram EMI indicates that the measurements are based on electromagnetic induction from coils (slingram is a Swedish word roughly meaning "loop frame").

For practical reasons, these EM instruments measure the electrical conductivity of the soil. Electrical conductivity, σ, is defined by Ohm's law, $i = \sigma E$ where i is the current density, i.e., the sum of electrical charges crossing the surface during some unit of time, and E is the electric field. Conductivity is expressed in Sm^{-1} (siemens per meter) and is dependent on the material through which the current passes. Conductivity is just the reciprocal of resistivity, that is $\sigma = 1/\rho$. With normal soils and typical frequencies of excitation, the low induction number (*LIN*) approximation will be valid. Then, the field at the secondary coil is directly proportional to the *IN* and thus proportional to the conductivity of the soil.

Most, if not all, electromagnetic instruments can measure either the electrical conductivity or the magnetic susceptibility of the soil, simply by changing a switch. This distinction is possible because of the phase, or time lag, of the oscillating magnetic field that is received from the soil by the instrument. The soil's susceptibility creates a magnetic field that oscillates exactly in synchronism with the field that is transmitted into the soil; this is called the "in-phase component" of the field. However, conductive strata in the soil generate a magnetic field that is delayed relative to the transmitted field; this is called the "quadrature component" of the field. Electronic circuitry in the EM instrument allows these two components to be separated. Finally, these instruments can also detect metallic objects, so they are excellent tools for archaeological prospection.

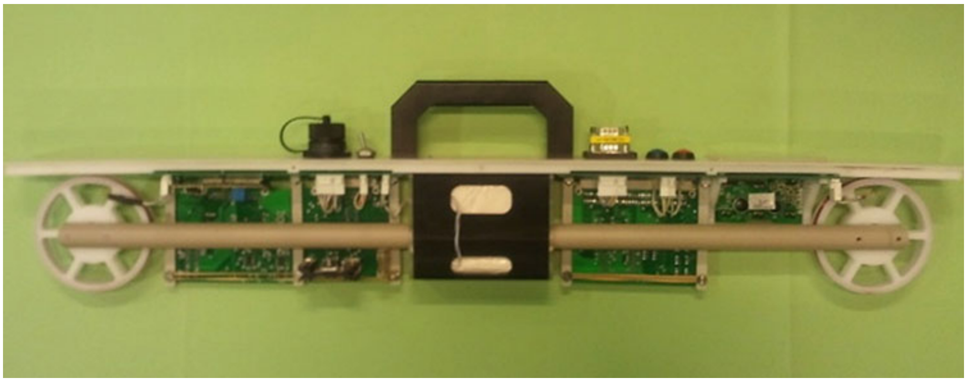
The relative orientation of the coils must be considered. First, some orientations will yield no response over a homogeneous, or planar-stratified ground, and this creates a disadvantage because the configuration yields no absolute values of conductivity or magnetic susceptibility, which are important for characterizing below-ground archaeological features and their host medium. The three relative orientations of a pair of coils that have been found to be most suitable for near-surface prospection are shown in Figure 8. In the HCP (horizontal coplanar) configuration, the two coils are on the same horizontal plane, their axes being vertical. In the VCP (vertical coplanar) configuration, the two coils are on the same vertical plane, and their axes are both horizontal. In the Perp (perpendicular) configuration, the two coils are in perpendicular planes, one having a vertical axis, the horizontal axis of the second being 90° from this axis. The same instrument can be used in both HCP and VCP orientations by a simple rotation of both coils; it can also be used in the vertical position (with the line between the transmitter and receiver coils vertical) (Thiesson et al., 2011). While the HCP configuration has the greatest sensitivity to deep conductive layers, it has two major faults: (1) the in-phase response of a magnetic layer exhibits a sign change at a depth of $z = 0.38\,L$, and (2) small conductive features yield readings of apparent conductivity that are less than that of the feature.



Electrical Resistivity and Electromagnetism, Figure 8 Different configurations (orientations) of the coils that are applied to near-surface prospection. In HCP, two coils lie in one horizontal plane but with vertical axes; in VCP, two coils lie in one vertical plane but with horizontal axes; in Perp, two coils lie in perpendicular planes, one with its axis vertical, the other with its axis horizontal and oriented 90° from that of the first.

The most suitable orientations for archaeological prospection are VCP and Perp, with Perp having a greater sensitivity to soil contrasts (Scollar et al., 1990). When comparing the relative advantages of the DC electrical method and the slingram EMI method in terms of feature detection, two points must be emphasized. First, with EMI, the detection of conductive features is easier than the detection of resistive features (Thiesson et al., 2009), and with the electrical method, the study of resistive targets is more reliable. Second, there is a question regarding their respective depths of investigation: in other words, which array size for a DC resistivity survey would give the same exploration depth as an L-spacing between coils of an EMI instrument? This question has neither a simple nor a general answer, but for an elongated resistive body of width L, a coil separation of L in the VCP configuration gives an anomaly whose width (measured at full-width half maximum) is about the same as an L-sided square array, although its anomaly is smaller in amplitude.

EM prospecting has the major advantage of allowing magnetic susceptibility measurements to be combined with magnetic field data in an interpretation (Pétronille et al., 2010). A picture of a small slingram EMI instrument, the CS60, is shown in Figure 9. In the field, it can be used in both the HCP and VCP orientations. It can also take its measurements while being pulled continuously on a sledge, or measurements can be made point by point.



Electron Probe Microanalyzer, Figure 9 The CS60 instrument without its casing. This instrument measures conductivity and susceptibility with a 60 cm inter-coil spacing in the VCP configuration (Courtesy of UMR Métis, UPMC; instrument designed by S. Flageul and J. P. Pencolé).

Conclusion

Electrical resistivity is the most variable parameter among those used in geophysical prospection; it allows the detection of a wide variety of archaeological features using quite simple (and inexpensive) measurement techniques. The DC electrical resistivity method allows a rapid approximation of the three-dimensional shapes of different archaeological targets, and it can be operated in small areas as well as large, open areas where mechanized techniques can be employed. Where the application of DC methods is difficult due to insufficient galvanic contacts, the electrostatic or electromagnetic methods can substitute; the EM technique has the advantage of simultaneously measuring conductivity and magnetic susceptibility.

Bibliography

Brinon, C., 2012. *Etude de la ressource en eau du site gallo-romain de Grand (Vosges) et de sa gestion antique*. Paris: Thèse Université Pierre et Marie Curie.

Brinon, C., Simon, F.-X., and Tabbagh, A., 2012. Rapid 1D/3D inversion of shallow resistivity multipole data: examples in archaeological prospection. *Geophysics*, **77**(3), E193–E201.

Campana, S., and Piro, S. (eds.), 2009. *Seeing the Unseen: Geophysics and Landscape Archaeology*. Boca Raton: CRC Press.

Caraire, G., Durand, J., and Jubeau, T., 2011. *L'agglomeration des Tours Mirandes (Vendeuvre-du-Poitou, 86), de la prospection gé ophysique à la fouille archéologique. Archéométrie 2011: XVIIIe Colloque d'Archéométrie du GMPCA (Groupe des Méthodes Pluridisciplinaires Contribuant à l'Archéologie), Liège, 11–15 avril 2011, Programme et Résumés*. Liège: Université de Liège, Facultés Notre Dame de la Paix, Namur, Groupe des Méthodes Pluridisciplinaires Contribuant à l'Archéologie, pp. 120–121.

Clark, A., 1996. *Seeing Beneath the Soil: Prospecting Methods in Archaeology*. London: Batsford Press.

Gaffney, C. F., and Gater, J. A., 2003. *Revealing the Buried Past: Geophysics for Archaeologists*. Stroud: Tempus.

Panissod, C., Dabas, M., Florsch, N., Hesse, A., Jolivet, A., Tabbagh, A., and Tabbagh, J., 1998. Archaeological prospecting using electric and electrostatic mobile arrays. *Archaeological Prospection*, **5**(4), 239–251.

Pétronille, M., Thiesson, J., Simon, F.-X., and Buchsenschutz, O., 2010. Magnetic signal prospecting using multiparameter measurements: the case study of the Gallic site of Levroux. *Archaeological Prospection*, **17**(3), 141–150.

Scollar, I., Tabbagh, A., Hesse, A., and Herzog, I., 1990. *Archaeological Prospecting and Remote Sensing*. Cambridge: Cambridge University Press.

Souffaché, B., Cosenza, P., Flaguel, S., Pencolé, J.-P., Seladji, S., and Tabbagh, A., 2010. Electrostatic multipole for electrical resistivity measurements at decimetric scale. *Journal of Applied Geophysics*, **71**(1), 6–12.

Thiesson, J., Dabas, M., and Flageul, S., 2009. Detection of resistive features using towed slingram electromagnetic induction instruments. *Archaeological Prospection*, **16**(2), 103–109.

Thiesson, J., Rousselle, G., Simon, F. X., and Tabbagh, A., 2011. Slingram EMI prospection: are vertical orientated devices a suitable solution in archaeological and pedological prospection? *Journal of Applied Geophysics*, **75**(4), 731–737.

Cross-references

Ground-Penetrating Radar
Magnetometry for Archaeology
Susceptibility

ELECTRON PROBE MICROANALYZER

J. Victor Owen
Department of Geology, Saint Mary's University, Halifax, NS, Canada

Synonyms

Electron microprobe (EMP); Microprobe; Probe

Definition

Electron probe microanalyzer: a microbeam instrument primarily used for in situ, generally nondestructive, chemical analysis and imaging of minute (micron scale) parts of solid media, including minerals, ceramics, glass, metals, and alloys, and biological materials (e.g., biopolymers such as chitin, cellulose, and encapsulating agents, especially those containing metals).

Introduction

The electron probe microanalyzer (henceforth "EPMA") essentially is a scanning electron microscope (SEM) equipped with wavelength (WDS)- and/or energy (EDS)-dispersive spectrometers. Thus, it provides high-resolution images of the medium being analyzed, as well as precise, quantitative, analytical data on a micrometer scale. As its name implies, the EPMA makes use of a tightly focused electron beam – as little as 1 micrometer (μm) or 1×10^{-6} m – to irradiate samples being investigated. The principal advantage of the EPMA is that it can be used to analyze samples of minute volumes in situ, so textural and microstructural features are preserved. Furthermore, the small "spot" size of the electron beam ensures that individual phases in extremely fine-grained materials can be analyzed and compositional zoning in larger grains can be quantified. The EPMA can also be used to generate elemental X-ray images (concentration maps), as well as bulk compositional data for extremely fine-grained samples.

If suitable standards are available, the EPMA can provide reproducible analytical data for elements heavier than lithium (i.e., atomic number (Z) > 3) at concentrations as low as ~100 parts per million (ppm). Where equipped with appropriate software, the instrument can be used to collect images of domains being analyzed. These images can then be subjected to quantitative image analysis to determine, for example, the proportion of phases (modal composition) in polymineralic materials. The same approach can be used to determine the modal composition of individual grains in a crystalline rock that contain an immiscible phase, so that the composition of the exsolved mineral can be numerically reintegrated back into its host. This is a first step in the application of some mineral thermometers (wherein mineral compositions are used to determine paleotemperatures). A more time-consuming approach involves rastering grains containing the exsolved phase (e.g., Bohlen and Essene, 1977).

Not all solids can be easily analyzed by the EPMA. Materials containing abundant volatiles can be unstable at the high-vacuum (~$2\text{–}5 \times 10^{-6}$ Torr) conditions in the microprobe chamber. Volatile components tend to decompress explosively when subjected to heating by the electron beam, thus potentially resulting in irreparable damage to the specimen. Strongly insulating materials can be damaged because they cannot quickly dissipate heat produced during irradiation by the electron beam, although this effect can be mitigated by coating in a highly conductive medium such as Al. Similarly, hydrocarbon-based media should not be analyzed because they are readily damaged by the electron beam, and they can contaminate the instrument.

Principle

The fundamental principle on which EMP analysis operates was discovered by H. G. J. Moseley (1887–1915), one of the leading young British physicists of his era. Moseley demonstrated that the frequencies of characteristic X-rays generated by particular elements vary linearly with the square root of the atomic numbers of those elements. This discovery, known as Moseley's law, supported models of the atom that had been proposed by Niels Bohr and A. J. van den Broek, and it showed that the atomic numbers of the elements are not arbitrary but are based on measureable attributes. Moseley recognized the potential of his discovery for analytical chemistry and for predicting elements missing (at the time) from the periodic table.

With regard to EPM analysis, the most important of the interactions between the electron beam and the sample occurs when incident beam electrons cause one or more inner shell electrons to be ejected from irradiated atoms. These inner shell vacancies leave atoms in a high-energy excited state. This excess energy is dissipated as (1) an outer shell electron fills the inner shell vacancy or (2) an outer shell (Auger) electron is ejected. The first mechanism releases an X-ray photon with energy equal to the difference in energy between the inner and outer shell electrons involved in this process. This is usually on the order of 0.1–15 keV. For specified inner/outer shell electrons, the energy of the emitted X-ray photon increases with atomic number (Z) because the higher positive charge of the atomic nucleus (i.e., number of protons) causes the electrons in all shells to be tightly bound, and this influences the energy of the emitted X-ray photons. Thus, each element produces X-rays with a characteristic energy or wavelength as they are irradiated. This phenomenon is exploited by the EPMA. The two characteristic X-ray lines most commonly used in microprobe analysis are $K\alpha$ and $L\alpha$, where, by X-ray notation, shells are labeled K, L, M, N, and O (from the lowest ground-state energy to the innermost shell outward). Electrons in the innermost shells have the highest ionization energies, and, in general, K X-rays have higher energies than L X-rays, and L X-rays have higher energies than M X-rays for any given element.

How it works

Electron microprobe analysis is based on the effects that a tightly focused and accelerated electron beam (5–30 keV) has on solid media. These include the generation of heat, secondary and backscattered electrons, continuum X-ray radiation (bremsstrahlung: German for "braking radiation"), cathodoluminescence, and, significantly, characteristic X-ray radiation. The emitted X-rays are counted by wavelength- and/or energy-dispersive spectrometers and compared with the intensity of characteristic X-rays generated during the analysis of standards (materials of known composition). Each wavelength-dispersive spectrometer contains specifically oriented diffraction crystals of known d-spacing that are sequentially positioned at angles determined by Bragg's law to diffract the X-ray wavelengths specific to particular elements toward a detector. WDS typically uses several gas-flow or sealed proportional detectors to count specific wavelengths; EDS uses a single solid-state semiconductor detector to accumulate X-rays of all energies (wavelengths) generated by the sample. Thus, EDS generates information about all elements in the analyzed sample simultaneously, whereas WDS will determine the concentration of only those elements selected by the user for analysis. Because of its superior X-ray peak resolution, the precision of WDS data is better than EDS data.

In WDS, the X-ray photons released by each element are counted for a length of time specified by the user. No single crystal satisfies Bragg's equation for all wavelengths, so most instruments have several spectrometers. Since the concentrations of elements sought by individual crystals are determined sequentially, WDS analysis is relatively slow compared to EDS. Depending on the number of elements being sought and count times, individual spot analyses determined by WDS typically take between 2 and 20 min to complete. Count data must be corrected for matrix effects (absorption and secondary fluorescence) to yield reliable quantitative analyses.

History

Moseley's experiments made use of an electron gun housed in a vacuum. Characteristic X-ray lines emitted by the irradiated samples were measured photographically. This apparatus has been described (Malissa, 1970) as the first EPMA. Subsequently, Manfred von Ardenne (1907–1997) measured backscattered electrons generated by a focused electron beam. In 1947, James Hiller (1915–2007), one of Canada's most distinguished scientists, patented the idea of using a focused electron beam as the basis for generating characteristic X-ray lines as an analytical tool. Shortly thereafter, Raimond Castaing (1921–1999), a French Ph.D. student, and his supervisor, Robert Guinier, constructed two prototypes, one for their own use and the other for a metallurgical laboratory (Grillon and Philibert, 2002). This equipment used a quartz crystal fitted to a Geiger counter to discriminate the wavelengths of secondary X-rays generated by particular elements (Newbury, 2001). In his Ph.D. thesis, Castaing reported both practical and theoretical aspects of the instrument, including a discussion of matrix corrections, and its applications to crystallography and metallurgy. Because of their contributions, Castaing and Guinier are generally considered to be the fathers of the modern EPMA.

A more complete history of the EPMA is provided by Mulvey (1983).

The instrument

The modern EPMA consists of four main components: a source of electrons (a tungsten or lanthanum boride filament), an electron-optic focusing system comprising electromagnetic lenses, a sample chamber that houses a stage that can be manipulated by the analyst using a joystick, and one or more wavelength- and/or energy-dispersive spectrometers. The sample chamber and electron-optic system are held to a high vacuum, so samples are loaded and removed via an external housing (air lock) that can also have its atmosphere evacuated. This procedure takes several minutes. Depending on its design, the turret holding samples and standards can usually accommodate several thin sections or grain mounts. These are viewed either directly with an optical-fiber-equipped optical microscope or using the instrument's electron imaging system, in which case the sample appears on computer monitors.

Use of the EPMA

In preparation for analysis, the instrument is calibrated (either by a technician or an experienced operator) for the elements to be sought. The appropriate operating conditions (e.g., beam current and accelerating voltage) are set, as is the electron beam diameter.

Samples are loaded onto a sample holder (turret), which is then inserted into an interlock chamber from which the air is then evacuated. A standard usually accompanies the "unknown" samples for quality control purposes. The turret is then loaded into the main chamber of the microprobe and positioned for analysis using a joystick to adjust X-Y coordinates. To assist with positioning, it is helpful to have a sketch map of the turret and the samples it holds and to have marked (where appropriate) individual points on the samples that have been selected for analysis. Once a spot to be analyzed has been found, the surface of the sample must be focused (by adjusting the Z coordinate, again using the joystick) to ensure that the Bragg's condition for diffraction is satisfied. Depending on the type of instrument, the operator views the sample either as an optical or an electronic image (i.e., a backscattered electron or secondary electron image). For operators accustomed to petrographic microscopes, the electronic images can be problematic because their gray tones are based on mean atomic weight and will initially be unfamiliar compared to optical images of the same material. It also takes some time for inexperienced operators to adjust to the small field of view (typically $\sim 3 \times 3$ mm at minimum magnification). Thus, the operator must be well prepared before commencing a session on the microprobe; otherwise, he or she will waste machine time seeking the intended points to be analyzed.

Depending on the type of data to be acquired, individual points can be selected and stored in a stage file (which records their X-Y-Z coordinates), or, for raster-type analysis (e.g., for documenting zoning in individual crystals or for determining the bulk composition of fine-grained media), the end points of a line or grid pattern can be selected, along with the number or spacing of intermediate points. Inevitably, some individual rastered analyses will have to be rejected because, by happenstance, spot analyses will have overlapped a pore or a region from which material to be analyzed has been plucked during the sample preparation process, resulting in a low analysis total.

Advantages and disadvantages

The main advantage of the EPMA is that samples can be analyzed and imaged in situ at a micrometer scale. Imaging detectors include backscattered electron, secondary electron, and, in some instruments, cathodoluminescence. Precision and accuracy can be assessed through the repeated analysis of suitable standards. All but the lightest elements (H, He, and Li) can be detected and analyzed quantitatively.

The principal disadvantage of the EPMA concerns overlapping peaks of X-rays generated by some elements (e.g., $Ba[L_\alpha]$ and $Ti[K_\alpha]$). These overlapping peaks must be separated in order to distinguish between these particular elements. The valence of iron is another concern. The EPMA cannot distinguish different valence states of iron. The operator of the EPMA can choose to have total iron expressed as a particular valence state, but only one valence state at a time. Generally, total iron is expressed as Fe^{2+}. Regardless, oxidation ratios ($X_{Fe3+} = Fe^{3+}/(Fe^{2+} + Fe^{3+})$) cannot be directly determined. Consequently, X_{Fe3+} must be determined independently (e.g., by Mossbauer spectrometry) or, in the case of ferromagnesian minerals, calculated using crystal-chemical constraints. Not all such minerals are well suited to this procedure, however (e.g., Droop, 1987), and even where they are, the reliability of the calculated oxidation ratio will be strongly dependent on the quality of the analysis; inaccuracies in the determination of other components (notably Si in the case of silicate minerals) will directly affect the calculated oxidation ratio. The EPMA cannot distinguish polymorphs; distinction between such minerals can be achieved using a petrographic microscope or by X-ray diffraction. Neither can the EPMA be used to determine isotopic ratios, but it has been used to date minerals such as monazite that do not initially contain appreciable amounts of daughter elements (e.g., Scherrer et al., 2000).

Sample preparation

Samples to be analyzed by EPMA are usually prepared as polished thin sections or grain mounts. The mirrorlike, flat, polished surface of the prepared sample optimizes interaction between the electron beam and the sample and minimizes the likelihood that surface imperfections will scatter X-rays generated by the electron beam.

The polished samples should be thoroughly cleaned with a suitable solvent to remove oils that can lead to charging (a buildup of excess, static electron density) of the sample. Electrically insulating media such as silicate minerals need to be coated with a conductive material such as graphite prior to analysis, again to minimize charging. The charge is dissipated by connecting the surface of the sample to the sample holder with a metal (typically copper) tape or conductive paint (generally carbon or silver).

Applications to geoarchaeology

The EPMA is principally used by geologists and materials scientists. As such, it also has geoarchaeological applications, and a wide range of archaeological materials can be analyzed by this method. These include lithic artifacts, ceramics, glass, metals, and alloys.

In terms of raw materials, lithic artifacts can be subdivided into two categories: those consisting of volcanic glass (obsidian) and those consisting of crystalline rock. The use of lithic materials in geoarchaeological studies, however, is not confined to artifacts shaped by humans; it also includes volcanic ash deposits (tuff; tephra) used in constraining the absolute age of stratigraphic layers containing evidence of human activity (i.e., tephrochronology). This involves identifying on compositional grounds volcaniclastic deposits related to specific eruptions that have been independently isotopically dated (e.g., Tryon and McBrearty, 2002) or, in the case of more recent volcanic events, whose age is known from historical records. To be effective, individual deposits must be sufficiently distinctive that the geochemistry of their constituents (e.g., volcanic ash) can be distinguished from those comprising tephra deposits related to the same or other volcanic centers that were active at different times. Although usually applied to proximal deposits, the method can also be applied to relatively fine-grained, distal deposits (cryptotephra; Balascio et al., 2011). Case studies involving the EPMA tend to focus on the major and minor elements to characterize tephra geochemically (e.g., Tryon and McBrearty, 2002; Balascio et al., 2011) as well as obsidian artifacts (e.g., Rosen et al., 2005), but trace element concentrations can also be acquired using this method by employing longer count times. Substantially more precise trace element data with much lower detection limits can be determined for tephra by other methods – notably LAM-ICP-MS (laser ablation microprobe-inductively coupled plasma-mass spectrometry) – applicable to fine-grained media.

Analysis of crystalline rock artifacts using the EPMA focuses on determining mineral compositions. These data can be coupled with bulk compositional analyses of the same artifacts (generally acquired by other methods) for use in provenance studies, but a bulk compositional analysis may not always be required. In the case of lithic artifacts made from geochemically unusual rocks (e.g., alkali basalt), the compositions of their constituent minerals can be sufficient on their own to track down the source of the rocks from which they were made. For example, Mallory-Greenough et al. (1999) were able to trace the source of alkali basalt used to make some Egyptian vessels to a specific lava flow by comparing the compositions of pyroxenes, plagioclase, and other minerals as determined by EPM analysis.

Archaeological ceramics are well suited for analysis by the EPMA, but the specific type of data to be gathered for these materials depends in large part on their grain size. Bulk, major, and minor element compositions can be reliably determined only for the body of those ceramics with average grain sizes smaller than the diameter of the defocused electron beam used during analysis. Typically, this is in the order of a few tens of micrometers. So, reproducible bulk compositional data can be determined only for porcelains and fine earthenwares such as creamware. The bulk compositions of coarse earthenware (e.g., most red-colored earthenware) should be determined by other methods (e.g., XRF or ICP-MS). Of course, the compositions of glazes and of minerals in the body of both fine and coarse earthenwares can be determined using the EPMA.

The acquisition by EPM analysis of bulk compositional data for porcelain and fine earthenware involves rastering using a defocused electron beam; bulk analysis of coarse wares (i.e., with average grain sizes exceeding a few tens of micrometers) is not practical with this method. The minimum number of spot analyses required to ensure that the resulting data are reproducible can be assessed statistically (e.g., DeJong and Owen, 1999). The finer grained and more homogeneous the ceramic medium, the fewer will be the number of spot analyses required to generate reproducible major and minor element bulk compositions. Many such wares are slip cast, ensuring more homogeneous compositions than coarse wares whose pastes are mechanically mixed. However, some elements are preferentially partitioned into accessory minerals (notably heavy minerals such as Fe(Ti) oxides, zircon, and apatite) that, even if homogeneously distributed in the ware, they are, by definition, present only in very low concentrations. The low concentration of these phases presents a serious challenge in the acquisition of reproducible data for the concentrations of elements tied to these minerals, and a greater number of domains must be rastered to improve the precision and accuracy of these analyses.

A similar problem is encountered during the analysis of glazes containing refractory opacifiers and whiteners such as tin. Being refractory, such grains are incompletely resorbed by the glaze as it melts in the glost kiln. As with accessory minerals in the body of the ware, refractory minerals in the glaze tend to be present in low concentrations and may be inhomogeneously distributed. Moreover, the element(s) they contain may be confined to these grains. So, determining the concentration of these components in the glaze will require multiple spot analyses, the number of which must be assessed statistically. One solution to both of these problems lies in using a scanning electron microscope equipped with electron-dispersive spectrometer (e.g., a silicon drift detector) that allows a larger area to be scanned during each analysis. Count time can be increased accordingly. Recent work has shown that SEM/EDS (SDD) analysis can produce results comparable to those of EPMA/WDS analysis (Owen, 2012; Ritchie et al., 2012) for major and minor elements. Moreover, the software controlling this equipment can allow the operator to outline in detail the areas to be rastered, even if irregular in shape. EPMA/WDS analysis, however, still generates more accurate and precise data for components present only in trace concentrations.

Microprobe analysis has also revealed that the lead-rich glazes commonly found on archaeological ceramics can be compositionally zoned. Typically, the zoning is dominated by an increase in lead and a decrease in silica content outward toward the glaze surface. The investigator must decide how best to present these data. One approach is to report the compositions of the outer surficial, middle, and inner parts of the glaze and perhaps supplement these data with a more detailed compositional profile for a representative sample (e.g., Owen and Barkla, 1997). Alternatively, space restraints might require that measurements for several such profiles be collected and the data averaged. The fact that the glaze is zoned should nonetheless be reported to facilitate comparison of data acquired by other methods. This issue will become increasingly acute given the popularity of methods that analyze only the surfaces of artifacts. Chief among these is portable XRF, which is relatively inexpensive and simple to operate and can generate data consistent with other analytical methods (e.g., traditional XRF and INAA; see Millhauser et al., 2011).

The imaging capability of the EPMA is particularly advantageous in the study of archaeological ceramics. For example, an investigation of the microstructure and composition of phosphate phases in the eighteenth century, variably vitrified, phosphatic porcelain sherds, suggested the recycling of overfired wasters (Owen et al., 2011a). The same approach can be used to compare distinctive accessory minerals (e.g., titania polymorphs) in early ceramics and their suspected clay or temper sources (e.g., Owen et al., 2011b).

The EPMA is also well suited to the analysis of metals and alloys. Microprobe data have been used to confirm sampling procedures involved in the analysis of metal artifacts by other methods (e.g., INAA; Gordus et al., 1996), but they also have formed the basis for archaeometric/geoarchaeological studies. Owing to the importance of isotopic data (e.g., particularly lead isotopes) in provenance studies involving alloys, other analytical methods are commonly used in addition to the EPMA. For example, Dorais and Hart (2006) used microprobe data supplemented by lead isotopes determined by mass spectrometry to characterize the composition of a Roman bronze artifact and assess the likely source of metals used in its manufacture. Increasingly, however, other methods with lower detection limits than EPM analysis are presently being used to analyze archaeological metals and alloys (e.g., Guerra and Calligaro, 2003; Cooper et al., 2008).

Bibliography

Balascio, N. L., Wickler, S., Narmo, L. E., and Bradley, R. S., 2011. Distal cryptotephra found in a Viking boathouse: the potential for tephrochronology in reconstructing the Iron Age of Norway. *Journal of Archaeological Science*, **38**(4), 934–941.

Bohlen, S. R., and Essene, E. J., 1977. Feldspar and oxide thermometry of granulites in the Adirondack Highlands. *Contributions to Mineralogy and Petrology*, **62**(2), 153–169.
Cooper, H. K., Duke, M. J. M., Simonetti, A., and Chen, G. C., 2008. Trace element and Pb isotope provenance analyses of native copper in northwestern North America: results of a recent pilot study using INAA, ICP-MS, and LA-MC-ICP-MS. *Journal of Archaeological Science*, **35**(6), 1732–1747.
DeJong, L. S., and Owen, J. V., 1999. Reproducibility of electron-microprobe bulk analyses of fine-grained media: a case study using modern bone china. *Canadian Mineralogist*, **37**(1), 239–246.
Dorais, M. J., and Hart, G. L., 2006. A metallurgical provenance study of the Marcus Herennius military diploma. *BYU Studies*, **45**(2), 77–87.
Droop, G. T. R., 1987. A general equation for estimating Fe^{3+} concentrations in ferromagnesian silicates and oxides from microprobe analyses using stoichiometric criteria. *Mineralogical Magazine*, **51**, 431–435.
Gordus, A. A., Henderson, C. E., and Shimada, I., 1996. Electron microprobe and neutron activation analysis of gold artifacts from a 1,000 A.D. Peruvian gravesite. In Orna, M. V. (ed.), *Archaeological Chemistry: Organic, Inorganic, and Biochemical Analysis*. Washington, DC: American Chemical Society. American Chemical Society, Symposium Series, Vol. 625, pp. 83–93.
Grillon, F., and Philibert, J., 2002. The legacy of Raimond Castaing. *Microchimica Acta*, **138**(3–4), 99–104.
Guerra, M. F., and Calligaro, T., 2003. Gold cultural heritage objects: a review of studies of provenance and manufacturing technologies. *Measurement Science and Technology*, **14**(9), 1527–1537.
Malissa, H., 1970. The present status of electron probe microanalysis. *Pure and Applied Chemistry*, **21**(4), 479–496.
Mallory-Greenough, L. M., Greenough, J. D., and Owen, J. V., 1999. The stone source of predynastic basalt vessels: mineralogical evidence for quarries in northern Egypt. *Journal of Archaeological Science*, **26**(10), 1261–1272.
Millhauser, J. K., Rodríguez-Alegría, E., and Glascock, M. D., 2011. Testing the accuracy of portable X-ray fluorescence to study Aztec and Colonial obsidian supply at Xaltocan, Mexico. *Journal of Archaeological Science*, **38**(11), 3141–3152.
Mulvey, T., 1983. Development of electron-probe microanalysis – an historical perspective. In Scott, V. D., and Love, G. (eds.), *Quantitative Electron-Probe Microanalysis*. Chichester: Ellis Horwood, pp. 15–35.
Newbury, D. E., 2001. Castaing's electron microprobe and its impact on materials science. *Microscopy and Microanalysis*, **7**(2), 178–192.
Owen, J. V., 2012. Double corona structures in 18th century porcelain (1st patent Bow, London, mid-1740s): a record of partial melting and subsolidus reactions. *Canadian Mineralogist*, **50**(5), 1255–1264.
Owen, J. V., and Barkla, R., 1997. Compositional characteristics of 18th century Derby porcelains: recipe changes, phase transformations, and melt fertility. *Journal of Archaeological Science*, **24**(2), 127–140.
Owen, J. V., Hunter, R., Jellicoe, R., and Zierden, M., 2011a. Microstructures of phosphatic porcelain from sintering to vitrification: evidence from sherds excavated in Charleston, South Carolina. *Geoarchaeology*, **26**(2), 292–313.
Owen, J. V., Meek, A., and Hoffman, W., 2011b. Geochemistry of sauceboats excavated from Independence National Historical Park (Philadelphia): evidence for a Bonnin and Morris (c. 1770–73) provenance and implications for the development of nascent American porcelain wares. *Journal of Archaeological Science*, **38**(9), 2340–2351.
Ritchie, N. W. M., Newbury, D. E., and Davis, J. M., 2012. EDS measurements of X-ray intensity at WDS precision and accuracy using a silicon drift detector. *Microscopy and Microanalysis*, **18**(4), 892–904.
Rosen, S. A., Tykot, R. H., and Gottesman, M., 2005. Long distance trinket trade: Early Bronze Age obsidian from the Negev. *Journal of Archaeological Science*, **32**(5), 775–784.
Scherrer, N. C., Engi, M., Gnos, E., Jacob, V., and Liechti, A., 2000. Monazite analysis; from sample preparation to microprobe age dating and REE quantification. *Schweizerische Mineralogische und Petrographische Mitteilungen*, **80**, 93–105.
Tryon, C. A., and McBrearty, S., 2002. Tephrostratigraphy and the Acheulian to Middle Stone Age transition in the Kapthurin Formation, Kenya. *Journal of Human Evolution*, **42**(1–2), 211–235.

Cross-references

Inductively Coupled Plasma-Mass Spectrometry (ICP-MS)
Neutron Activation Analysis
Scanning Electron Microscopy (SEM)
Tephrochronology
X-ray Diffraction (XRD)
X-ray Fluorescence (XRF) Spectrometry in Geoarchaeology

ELECTRON SPIN RESONANCE (ESR) IN ARCHAEOLOGICAL CONTEXT

Mathieu Duval
ESR Dating Laboratory, Geochronology, Centro Nacional de Investigación sobre la Evolución Humana (CENIEH), Burgos, Spain

Synonyms

Electron paramagnetic resonance (EPR) dating

Introduction

Electron spin resonance (ESR) dating is a chronometric dating method, but depending on the author, it may also be classified as a radiation exposure, a trapped charge, a paleodosimetric, or a radiometric method. Like other methods that use luminescence phenomena, ESR is based on an evaluation of the exposure of some materials to natural radioactivity. This expsoure is expressed as an absorbed radiation dose, which corresponds to the energy deposited in the matter by ionizing radiation. Such materials can acquire or develop a paramagnetic behavior under the effect of natural radioactivity, which can be later detected and quantified by means of ESR spectroscopy.

Use of this technique for dating purposes was first suggested by Ikeya (1975) based on the study of stalactites from caves in Japan. Since then, numerous applications to a wide range of materials have been to varying degrees successfully attempted (see the extensive reviews in Grün, 1989; Rink, 1997), so that ESR dating has become a landmark in *Quaternary Geochronology*.

Basic principles

ESR spectroscopy is a technique based on the detection of unpaired electrons. Materials possessing unpaired electrons are paramagnetic. As a result, they can be affected by an externally applied magnetic field, which induces an alignment in the spin of some unpaired electrons and, consequently, in their magnetic dipoles. When the external magnetic field is removed, the alignment is not retained. To measure unpaired electrons, the sample to be tested is placed in a magnetic field and exposed to microwaves of a fixed frequency (Figure. 1a). At a given magnetic field value corresponding to specific conditions of resonance, the microwaves are absorbed by the unpaired electrons, and an ESR signal is detected (Ikeya, 1993). ESR spectroscopy is used in many scientific fields like biology, physics, chemistry, medicine, earth sciences, and archaeology, and it is now considered a key tool for studies dealing with biological and retrospective dosimetry (Regulla, 2005; Fattibene and Callens, 2010). Its application for dating purposes is directly derived from that branch of investigation. Indeed, in ESR dating, the sample acts as a dosimeter, i.e., a material that is able to register accurately the energy absorbed when exposed to natural radioactivity over geological time. The interaction of the sample with ionizing radiation (alpha and beta particles plus gamma and cosmic rays) emitted from the radioelements (mainly U, Th, and K) located within the sample and in its surrounding environment induces changes in the electronic structure of the material. Some electric charges (electrons or holes) become trapped in the crystalline network by lattice defects (impurities or vacancies in the solid material), producing radiation-induced paramagnetic species (i.e., free radicals or paramagnetic centers possessing unpaired electrons) which build up a characteristic signal that can be detected by ESR spectroscopy. The intensity of the ESR signal is proportional to the amount of trapped charges. The latter depends on three main parameters: the strength of the natural radioactivity in the sample and its surroundings, the duration of exposure to radiation, and the total number of traps available in the sample. An ESR age is derived from the following equation:

$$D_E = \int_0^T D(t)dt \tag{1}$$

In (1), D_E is the equivalent dose, or paleodose – expressed by the dosimetric unit Gray or Gy (which represents the absorption of 1 J of ionizing radiation per kilogram of matter) – i.e., the total dose absorbed by the sample during the time elapsed between the zeroing of the ESR clock ($t = 0$) and the sampling (t = T). D(t) is the dose rate (usually in Gy/ka or μGy/a), or annual dose, which is the average dose absorbed by the sample in 1 year. When the dose rate is constant over time, (1) may then be simplified as follows:

$$T = \frac{D_E}{D} \tag{2}$$

where T is the age of the sample.

Four main processes may lead to the elimination of paramagnetic species and then to the zeroing of the ESR clock (i.e., removal of accumulated charges by releasing the trapped electrons): (1) crystallization, (2) heat, (3) optical bleaching, and (4) mechanical stress (Ikeya, 1993). Depending on the kind of sample analyzed, the events that can be dated are consequently quite diverse, for example, death of an animal, a crystallization process, the last exposure to sunlight, or the last time a material was heated. Further details about the basic principles of the dating methods can be found in Grün (2007) and Ikeya (1993).

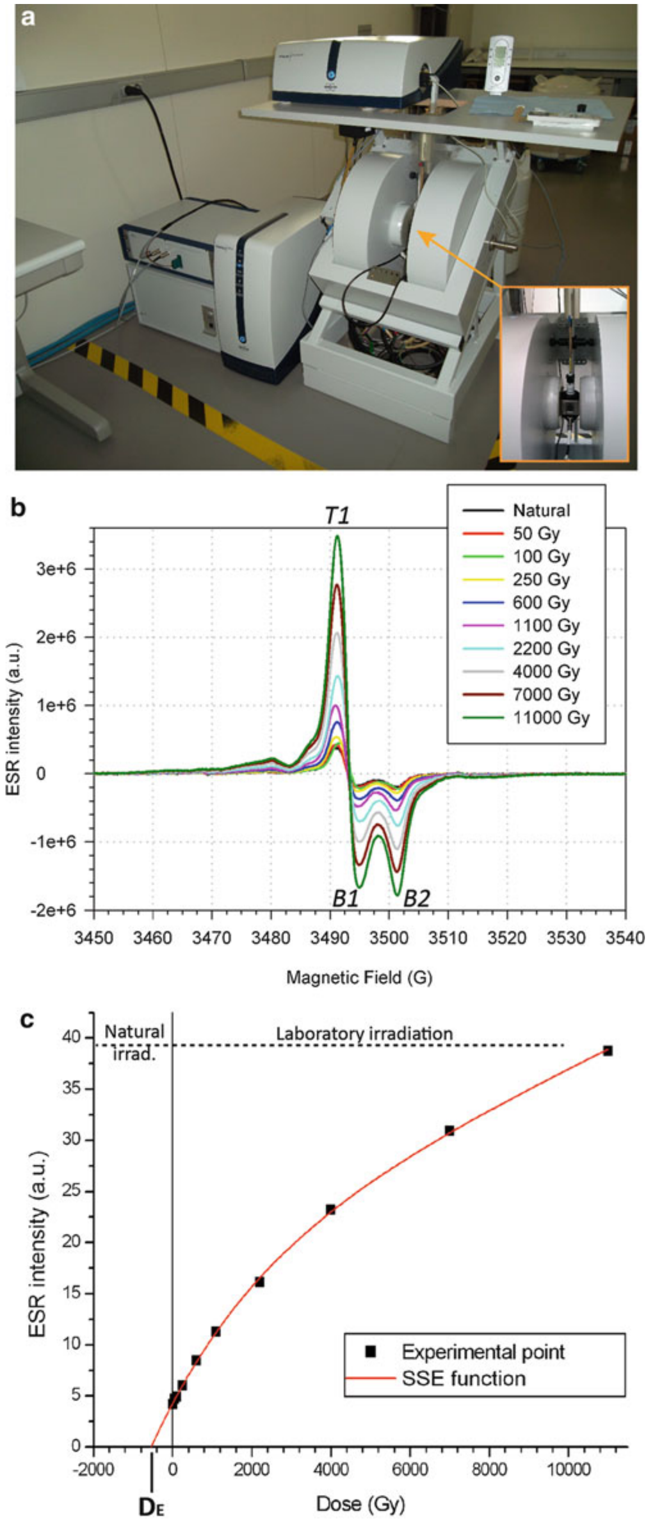
ESR age determination

An ESR age estimate is basically derived from the combination of two principal parameters: (1) the equivalent dose and (2) the dose rate. Nevertheless, to obtain these two parameters one must follow a long and complex analytical process made of several steps involving both field and laboratory procedures.

Sampling

Fieldwork is the first step of the dating process. It consists not only of the sampling but also in the collecting of all relevant information that may be useful at the time of data analysis and interpretation: stratigraphic and spatial location of the sample, sedimentary context, homogeneity, texture and composition of the sediment, depth of the sample, etc. Sampling itself can take many forms, depending on the kind of material to be analyzed (Grün, 1989). For example, it is important to minimize the exposure of raw sediment to sunlight when sampling for ESR dating of quartz grains. To accomplish this, several tactics can be employed: inserting a PVC tube into an outcrop or section, extracting an intact block of sediment for further preparation under stricter light conditions in the laboratory, or collecting the sediment under an opaque cover. For the dating of teeth, samples have usually already been recovered during an archeological or paleontological excavation and are thus chosen from collections. In that case, it is important to make sure that the selected tooth is well preserved and its findspot within the site is well known in order to avoid future problems during subsequent sample preparation and environmental dose rate reconstruction.

In addition, it is also advisable to carry out in situ measurements of the natural radioactivity at the place where the sample was collected, or the closest possible locality, in order to get an accurate estimation of the gamma dose rate. This is usually done using either synthetic TL dosimeters (e.g., $CaSO_4$:Dy, Al_2O_3:C) registering a total gamma dose rate over a long period (up to several months, e.g., Miallier et al., 2009 and references therein), or a portable gamma spectrometer with NaI or LaBr scintillation probes



Electron Spin Resonance (ESR) in Archaeological Context, Figure 1 (Continued)

(Arnold et al., 2012), which can identify the specific activities of each radioelement (energy windows technique Arnold et al., 2012) or provide a total gamma dose rate (threshold technique: Duval and Arnold, 2013) in a short amount of time (<30 min). Additional small bags of sediment are also usually collected for future laboratory analysis, in order to determine the water content or the radioelement concentration of the sediment surrounding the sample.

Sample preparation

The main goal of sample preparation always remains the same, whatever kind of sample is to be analyzed: to extract "pure" material (a few grams) with no contamination that would interfere with the intended analysis (ESR, U-series, etc.). The examples described by Grün (1989) show the wide range of tools and processes that may be employed (e.g., dentist drill, sieving, crushing, removal by chemical attack, etc.). In addition, preparation is often the opportune time to remove as much of the outer parts of the sample as possible in order to minimize or even eliminate the contribution of the external alpha and beta particles (see Dose rate assessment). Sample preparation usually ends when the sample is reduced to a powder prior to gamma irradiations (see later).

D_E reconstruction by ESR spectrometry

ESR spectrometry (equipment shown in Figure 1a) is used as a dosimetric tool to assess the DE value absorbed by the sample. The standard procedure involves artificially "aging" the sample by irradiating one or several subsample aliquots (single aliquot or multiple aliquot techniques) at various doses (additive dose method) in order to study the behavior of the ESR signal with increasing dose values (Figure 1b). A variant of this procedure is to reset the ESR signal to zero in the natural sample prior to any laboratory irradiation (regenerative dose method). The ESR intensity is extracted from the spectrum obtained for each aliquot (Figure 1b), and paired data (dose; intensity) are plotted as shown in Figure 1c. Then, a curve may be fitted to the experimental data points in order to describe the growth behavior of the samples versus absorbed dose. Further details about this fitting procedure may be found in Duval et al. (2009) and references therein. Assuming that the ESR intensity was null at $t = 0$, i.e., usually at the moment of formation or burial of the sample, the extrapolation of the curve to the abscissa axis ($Y = 0$) leads to the D_E value accumulated in the sample since $t = 0$ (Ikeya, 1993) (Figure 1c).

ESR measurements are usually carried out with an X-band spectrometer (microwave frequency ~9.8 GHz) on a powdered sample (with grain size between 50 and 500 μm) in order to remove, or at least minimize, the angular dependence of the ESR signal within the cavity (see Figure 1a) and to improve sample homogeneity and thus data reproducibility. Nevertheless, some efforts have been made in the past 20 years to reduce the destructive aspect of the dating method and to minimize the amount of material needed (e.g., by using the regenerative dose technique, a single aliquot procedure, carrying out ESR measurements on single crystals, or using Q-band spectrometers). For example, the combination of ESR measurements on enamel fragments with laser ablation ICP-MS U-series analysis allows determinations to be conducted on fossil human teeth without causing any visible damage (Grün et al., 2006).

Dose rate assessment

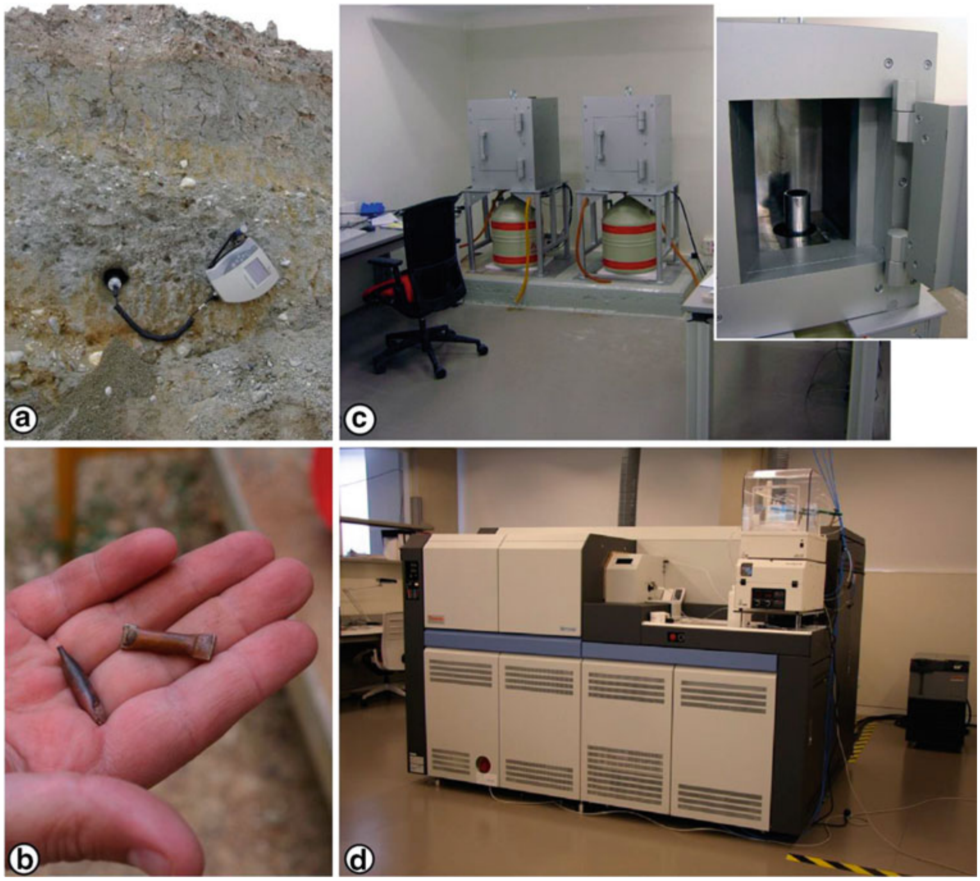
Dose rate is obtained from the assessment of the natural radioactivity of the sample itself (internal dose) and its surrounding environment (external dose + cosmic dose) (see Figure 5 from Grün, 2007). It may be expressed as follows:

$$D = D_{int.} + D_{ext.} + D_{cos.} = D_\alpha + D_\beta + D_\gamma + D_{cos.} \quad (3)$$

where $D_{int.}$, $D_{ext.}$, and $D_{cos.}$ are the internal, external, and cosmic dose rate, and D_α, D_β, D_γ are the alpha-particle, beta-particle, and gamma-ray contributions to the total dose rate (D), respectively. Depending on the size and the geometry of the dated sample, however, some specificities need to be carefully considered. Indeed, the weighting of the contribution of each component may vary greatly, given the ranges of alpha (~20–40 μm) and beta particles (~2 mm) and gamma rays (~30 cm) in matter such as sediment (see Grün, 1992 for further details).

Usually, the dose rate is derived from the activities, expressed in becquerels (Bq/kg), or disintegrations per minute per gram (dpm/g), or concentrations, expressed in parts per million (ppm) or percentage (%) of the radioactive elements (U, Th, and K) present in the sample and its surroundings. Those values may be obtained in the laboratory using different techniques (Goldstein and Stirling, 2003, and references therein), such as measuring either the

Electron Spin Resonance (ESR) in Archaeological Context, Figure 1 ESR dose reconstruction (**a**) EMXmicro-6/1 (X-band) Bruker ESR spectrometer. *Bottom right*: zoom on the cavity (or ESR resonator) located between the magnets and where the tube containing the sample is inserted for ESR measurements. (**b**) Evolution of the ESR spectra of tooth enamel with the irradiation dose (the magnetic field is expressed in Gauss). The ESR intensities are extracted from each ESR spectrum by measuring peak-to-peak amplitudes between T1 and B2 peaks. (**c**) D_E determination involves the following steps: (i) ESR intensities (experimental points) are plotted versus the irradiation doses, (ii) a single saturating exponential (*SSE*) function is fitted through the experimental data points, and (iii) the curve is extrapolated to $Y = 0$ in order to get the D_E value. Graph c is usually defined as a dose response curve (*DRC*).



Electron Spin Resonance (ESR) in Archaeological Context, Figure 2 Examples of techniques that may be used in the field (**a**, **b**) or in the laboratory (**c**, **d**) to assess the dose rate: (**a**) Field measurement using a portable gamma spectrometer (Canberra InSpector 1000 multichannel analyzer connected to a LaBr3:Ce probe). (**b**) TL dosimeters ($CaSO_4$:Dy) encapsulated in copper. (**c**) High-purity Germanium detectors (Canberra) for high-resolution gamma spectrometry analysis of the natural radioactivity of geological and/or archeological samples. (**d**) ThermoFinnigan Neptune multi-collector (*MC*) inductively coupled plasma mass spectrometry (*ICP-MS*).

emitted energy derived from the disintegrations (e.g., α-spectrometry and γ-spectrometry) or directly from the isotopes using mass spectrometry (e.g., TIMS, ICP-MS) (Figure 2). Then, these data are converted into dose values with published factors (Guérin et al., 2011, and references therein). Another way of proceeding is to obtain a total beta or gamma dose rate value directly by using a beta counter (see, e.g., Ankjærgaard and Murray, 2007). In addition, as previously explained, the external dose due to sediment resting adjacent to the sample can also be assessed in situ (Figure 2). Then, the data characteristics of the sample and its surrounding environment have to be adjusted using various correction factors relating to parameters such as water content, the geometry of the sample, its thickness and density (α-attenuation, β-attenuation, and γ-attenuation), and the alpha efficiency (α-particles are high-energy particles that are less effective in producing an ESR signal than beta particles or gamma rays, and thus the alpha efficiency must be estimated as the fraction of an equivalent beta or gamma dose that would yield the same ESR intensity) (Aitken, 1985; Grün, 1989; Ikeya, 1993). Similarly, the cosmic dose has to be adjusted according to various factors, like the ground density, depth of the sample, elevation, and latitude (Prescott and Hutton, 1994, and references therein). In addition, it is known that some materials (e.g., fossil teeth, corals, mollusk shells) behave as open systems for uranium, which means that U may be incorporated or leached at any time. In that case, U-uptake needs to be modeled by using, for example, both U-series and ESR data to get a combined U-series/ESR age estimate (Grün, 2009a). U-series disequilibrium in sediment may also be detected and have a significant impact on the dose rate estimate (Olley et al., 1996).

Evaluation of the dose rate is based on the analysis of present-day data extracted from the sample and its surrounding environment, and such data are considered as representative of the past history; either they are assumed to have been constant over time or following a trend that can be accurately assessed. Otherwise, if not detected, any substantial modification of the sample or its surroundings by diagenetic processes (e.g., dissolution/recrystallization processes, recent U-mobilization, water circulation, reworked sediment, etc.) can introduce a bias into the dose rate assessment. Careful sampling is therefore an important starting point in the analytical process, as it can help to minimize future potential uncertainties that may affect the ESR age estimation.

ESR age estimate

Once all the above data have been collected, the age calculation may be processed by simply dividing the equivalent dose value by the dose rate. Some guidelines about the error assessment may be found in Aitken (1985); however, for samples that require modeling (e.g., for uranium uptake in dental tissues), the age calculation becomes more complicated, and some iterative computations are necessary. Noncommercial programs for ESR age calculation are available on request from the scientists who developed them. For example, the DATA program (Grün, 2009b) and its Matlab equivalent USESR (Shao et al., 2014) permit combined U-series/ESR age calculation for teeth (Grün, 2009b) and also for coral or mollusks, as soon as the alpha efficiency is adjusted. The ROSY software is another program option (Brennan et al., 1999).

ESR ages are usually quoted at 1-sigma, and final errors are rarely <10 % (Rink, 1997) – more likely, they lie between 10 % and 20 %. This is mainly due to the numerous parameters (sometimes more than 20) that must be considered and adjusted for the age calculation process (among others: D_E, water content, radioelement content, alpha efficiency, density, cosmic dose, gamma dose). Reviews may be found in Grün (1989, 1992).

Potential of ESR dating

ESR dating shows great potential for *Quaternary Geochronology*, since it can theoretically cover the last 2.6 Ma in any geological context. One of the major strengths of ESR dating is the wide range of materials that can potentially be dated with it (Ikeya, 1993). Such materials include, among others, carbonates (e.g., speleothems, coral, shell, foraminifera), sulfates (e.g., gypsum), phosphates (e.g., fossil tooth), silica (e.g., quartz extracted from sediment, volcanic rock, or geological faults – to date the tectonic event based on zeroing of the ESR clock due to mechanical stress reset), or other silicates (e.g., clay minerals, feldspars). Every material with dosimetric properties, i.e., showing the creation of paramagnetic centers under the effect of natural radioactivity, may potentially be used for ESR dating if it fulfills the six criteria (Grün, 1989, 2007):

1. The selected ESR signal is equal or (re)set to 0 at $t = 0$;
2. Its intensity increases proportionally with the absorbed dose (radiation sensitivity);
3. The ESR signal has a lifetime at least one order of magnitude higher than the age of the sample;
4. The number of traps remains constant over time (i.e., no dissolution, recrystallization, or crystal growth processes have occurred);
5. The selected ESR signal does not show anomalous decay over time (fading) under normal conditions of measurement and storage;
6. The ESR signal is not influenced by sample preparation, unless the impact can be controlled and quantified.

With relatively modern samples, the dating limits for the most recent $t = 0$ are mainly driven by: (i) the radiation sensitivity of the material, and (ii) the sensitivity of the instrumentation employed for dose reconstruction, including the ESR spectrometer. As an example, for tooth enamel samples, the smallest dose value ever detected was of ~0.46 mGy (lower detection limit) (Romanyukha et al., 2005), suggesting a possible dating application up to and including even present-day materials. For speleothems, an older dating limit around 2 ka (Bassiakos, 2001) or even less (Grün, 1989) has been determined.

In contrast, the upper dating limit is mainly constrained by two parameters. The first one is the saturation of the ESR signal with the absorbed dose. Depending on the number of traps available in the crystal lattice and the nature of the paramagnetic center that is analyzed, the intensity of the ESR signal will saturate more or less quickly when the material is absorbing ionizing radiations. The second parameter is the thermal stability of the paramagnetic centers, which describes the mean life of a trapped electron at a lattice defect site. In general, one considers that the ESR signal must have a mean life at least one order of magnitude higher than the age of the sample dated (Grün, 2007). As an example, Schwarcz (1985) assessed the lifetime of the ESR signal of tooth enamel to ~1 Ga at 25 °C, suggesting a possible application over a few million years. In quartz, the ESR signal associated with the aluminum (Al) paramagnetic center, the most widely used in geochronology, shows almost no saturation with doses up to 60 kGy (Lin et al., 2006) and stability over ~7.4 Ga at 27 °C (Toyoda and Ikeya, 1991) making it potentially useful for the entire Quaternary.

Examples of applications in archaeology

ESR is probably the only chronometric dating method that can be potentially used in almost any geological context. It may take over from some chronometric methods, like OSL dating, for alluvial terrace deposits older than ~200–300 ka or from U-series dating of carbonates in karstic environments over ~600 ka. Direct dating of hominin remains beyond the range of radiocarbon is also possible (Grün et al., 2010). As an example, in Europe, most archeological sites are not found in volcanic contexts, but either in karstic or alluvial environments where the use of a chronometric method like Ar-Ar is impossible because of the lack of coeval volcanic materials. For occupations older than mid-Middle Pleistocene (>500 ka), ESR is definitely the most widely used method, in particular for dating the first hominin settlements in Europe. The development of the method for Early Pleistocene times offers perhaps one of the most interesting perspectives (Duval et al., 2012), since this is a period when the number of chronometric dating methods is very limited, and those that exist are highly dependent on the geological context (Falguères, 2003).

There is a large and diverse list of published ESR dating applications in archeological contexts over the last ~20 years, most of which lie within the 50–500 ka time range. These dating studies are based principally on three kinds of materials that come from either open-air sites or caves: carbonates, phosphates, and silicates. Examples of applications are given hereafter, and the strengths and weaknesses of the most common ones, are detailed in Table 1.

ESR dating of speleothems is the oldest application of the method (Ikeya, 1975). As an example of a recent application, Valladas et al. (2008) obtained ESR age estimates using stalagmitic formations from the Neanderthal Payre Cave in France. The late Middle Pleistocene age results (<300 ka) were consistent with the corresponding U-series ages performed on the same unit. At Treugolnaya Cave in Russia, Molodkov (2001) dated several terrestrial shell samples from deposits associated with Early Acheulean lithic artifacts. They yielded an ESR chronology older than 350 ka. Similarly, Blackwell et al. (2012) dated mollusk shells correlated with Late Pleistocene archeological evidence in the Western Desert of Egypt. Such applications may potentially cover a time range from as recent as 5 ka to as old as >2 Ma (Molodkov, 2001; Blackwell et al., 2012), even if their reliability mainly depends on the accuracy of the U-uptake modeling.

ESR dating of fossil teeth (hydroxyapatite mineral) is surely the most famous application of the ESR method. It allows direct dating of animal and hominin occupations from the Early to Late Pleistocene time range (Table 1). Although the fossil teeth of large mammals are typically dated (e.g., Falguères et al., 2010), human teeth may be analyzed as well (e.g., Grün et al., 2006). One can consider the work of Torres et al. (2010) as an example. Part of a study combining various chronometric dating methods included the dating of a fragment of human incisor from El Sidrón Cave in Spain; the tooth material was dated by a semi-destructive analytical procedure based on the combination of ESR analysis with LA-ICP-MS U-series analysis. The ESR age estimate of 38.5 ± 4.5 ka was found to be in good agreement with the results derived from the other methods, like radiocarbon, U-series, OSL, and amino acid racemization, which ranged from 30 to 50 ka for the archeological unit (see further details in Torres et al., 2010). Geological occurrences of hydroxyapatite can also be dated, as illustrated by the work performed on authigenic terrestrial apatite veins at Tabun Cave in Israel, which provided useful information about the diagenetic processes that had occurred in the deposits (Rink et al., 2003).

Silicates, and especially quartz minerals, are also widely used for ESR dating. As with OSL dating, ESR can date optically bleached quartz grains extracted from sediments (Table 1). Quartz is a ubiquitous mineral that is found in almost any geological context. Because many Pleistocene archeological sites are situated in fluvial contexts (Mishra et al., 2007), ESR is often employed to date whole terrace systems where hominin occupation has been documented. As an example, Voinchet et al. (2010) dated several fluvial systems from central France between ~130 to ~1700 ka. As previously detailed, ESR is one of the few dating methods that can be applied to Early Pleistocene sites. For example, at the archeological site of Vallparadís in Spain, ESR was not only applied to quartz grains but also to fossil teeth (Duval et al., 2015, and references therein); both applications yielded consistent results around 0.8 Ma for the main archeological level. The resulting mean ESR age of 858 ± 87 ka was found to be in excellent agreement with the results derived from paleomagnetism and biochronology, which suggested a Matuyama age for the deposits, and more precisely between the Brunhes chron and the Jaramillo subchron (i.e., 0.99–0.78 Ma). Other applications to silicates are also documented. At the lower paleolithic site of Menez Dregan in France, Monnier et al. (1994) published an ESR chronology of ~350–400 ka based on heated quartz grains extracted from fireplace sediments and a burnt quartzite pebble. Similarly, ESR dating of burnt flint has also been studied. Porat and Schwarcz (1991) showed the potential of this application by dating some samples from Middle Eastern archeological sites. In addition, similarly to the thermoluminescence (TL) method, ESR may be used to date pottery firing. Bartoll and Ikeya (1997) analyzed fragments from a Neolithic vessel excavated in Rohrback, Germany: ESR age estimates of ~5 ka were in agreement with the TL ages obtained on the same fragments, even if they showed larger errors than the TL age results.

Summary

ESR dating is a paleodosimetric method based on the detection and quantification of the trapped charges accumulated over time in the crystal lattice of some materials due to their exposure to natural radioactivity. Perhaps more than any other chronometric method, ESR can be used in a very broad variety of archeological applications covering almost any geological context during the last 2.6 Ma. Among them, ESR dating of fossil tooth enamel, sedimentary quartz grains, and speleothems are probably the most promising, since these materials are commonly found in association with archeologically significant remains.

Electron Spin Resonance (ESR) in Archaeological Context, Table 1 Summary of the potential and limitations of the three main ESR dating applications in archeological contexts: fossil teeth, optically bleached quartz grains extracted from sediment, and speleothems. Key: *LLD* lower limit of detection, i.e., the minimum dose that can be assessed by ESR.

	Fossil tooth enamel	Optically bleached quartz grains extracted from sediment	Speleothem (stalagmite, stalactite, flowstones)
Dated event	Death of the animal/burial of the fossil tooth	Last sunlight exposure of the sediment	Formation of the speleothem
Main specificity of the application	Dental tissues are open systems for U: U-uptake needs to be modeled	Optical dating method (same basic principles as OSL dating)	Speleothems are usually closed systems for U: no specific U-uptake has to be modeled
		Presence of a residual (non-bleachable) ESR intensity for the Al -center	
Lower dating range	Present-day (LLD = 0.46 mGy; Romanyukha et al., 2005)	~10 ka (Ti-center; Beerten et al., 2003) (LLD = a few tens of Gy, Ti-center; Beerten and Stesmans, 2005)	~500–2,000 a (LLD = 1.6–1.8 Gy; Bassiakos, 2001)
Upper dating range	Early Pleistocene (e.g., Duval et al., 2012)	Miocene (Al-center) (e.g., Laurent et al., 1998)	~1–2 Ma (e.g., Yokoyama et al., 1988)
Strengths of the application	Fossil teeth are frequently found in archeological contexts	Quartz mineral is found in almost any geological context	Material frequently found in caves
	ESR dosimetry of tooth enamel is now international reference method (Fattibene and Callens, 2010)	Great potential in fluvial contexts, where bleaching conditions are usually optimum (e.g., Voinchet et al., 2007), and evidence of human occupation are frequent (Mishra et al., 2007)	Can date beyond the U-series dating time range
	Direct dating of hominin and animal fossil remains	May date beyond the OSL dating time range	
	Can date beyond the C-14 and U-series dating time range (Grün et al., 2010)	Several paramagnetic centers may be used for geochronology (see Ikeya, 1993): Al, Ti, E′, etc.	
	Semi-destructive method, when combining ESR on enamel fragment with LA-ICP-MS U-series analysis (Torres et al., 2010)		
Weaknesses of the application	Complexity of the analytical process (e.g., U-series analysis is needed for each dental tissue)	Technological limitations: Single-grain ESR measurements are complicated (e.g., Beerten et al., 2003); ESR data are not as reproducible as those obtained for enamel samples (e.g., quite strong angular dependence of the ESR signal in the cavity)	Debate about the choice of a reliable and stable ESR signal (e.g., Grün, 1989)
	Difficulty to locate precisely (geographically and stratigraphically) the sample's origin in case of old excavations		Compared with ESR, U-series dating offers several advantages: a relatively fast and standardized analytical procedure leading to the production of more precise age results.
	Quite low precision (standard errors are usually >10 %) in comparison with other chronometric methods like C-14, Ar-Ar and U-series (e.g., Ludwig and Renne, 2000)	Quite low precision (standard errors are usually >10 %) in comparison with other chronometric methods like C-14, Ar-Ar and U-series (e.g., Ludwig and Renne, 2000)	Quite low precision (standard errors are usually >10 %) in comparison with other chronometric methods like C-14, Ar-Ar and U-series (e.g., Ludwig and Renne, 2000)

Bibliography

Aitken, M. J., 1985. *Thermoluminescence Dating*. London: Academic.

Ankjærgaard, C., and Murray, A. S., 2007. Total beta and gamma dose rates in trapped charge dating based on beta counting. *Radiation Measurements*, **42**(3), 352–359.

Arnold, L. J., Duval, M., Falguères, C., Bahain, J.-J., and Demuro, M., 2012. Portable gamma spectrometry with cerium-doped lanthanum bromide scintillators: suitability assessments for luminescence and electron spin resonance dating applications. *Radiation Measurements*, **47**(1), 6–18.

Bartoll, J., and Ikeya, M., 1997. ESR dating of pottery: a trial. *Applied Radiation and Isotopes*, **48**(7), 981–984.

Bassiakos, Y., 2001. Assessment of the lower ESR dating range in Greek speleothems. *Journal of Radioanalytical and Nuclear Chemistry*, **247**(3), 629–633.

Beerten, K., and Stesmans, A., 2005. Single quartz grain electron spin resonance (ESR) dating of a contemporary desert surface deposit, Eastern Desert, Egypt. *Quaternary Science Reviews*, **24** (1–2): 223–231.

Beerten, K., Pierreux, D., and Stesmans, A., 2003. Towards single grain ESR dating of sedimentary quartz: first results. *Quaternary Science Reviews*, **22**(10–13), 1329–1334.

Blackwell, B. A. B., Skinner, A. R., Mashriqi, F., Deely, A. E., Long, R. A., Gong, J. J. J., Kleindienst, M. R., and Smith, J. R., 2012. Challenges in constraining pluvial events and hominin activity: examples of ESR dating molluscs from the Western Desert, Egypt. *Quaternary Geochronology*, **10**, 430–435.

Brennan, B. J., Rink, W. J., Rule, E. M., Schwarcz, H. P., and Prestwich, W. V., 1999. The ROSY ESR dating program. *Ancient TL*, **17**(2), 45–53.

Duval, M., and Arnold, L. J., 2013. Field gamma dose-rate assessment in natural sedimentary contexts using $LaBr_3$(Ce) and NaI (Tl) probes: a comparison between the "threshold" and "windows" techniques. *Applied Radiation and Isotopes*, **74**, 36–45.

Duval, M., Grün, R., Falguères, C., Bahain, J.-J., and Dolo, J.-M., 2009. ESR dating of lower Pleistocene fossil teeth: limits of the single saturating exponential (SSE) function for the equivalent dose determination. *Radiation Measurements*, **44**(5–6), 477–482.

Duval, M., Falguères, C., and Bahain, J.-J., 2012. Age of the oldest hominin settlements in Spain: contribution of the combined U-series/ESR dating method applied to fossil teeth. *Quaternary Geochronology*, **10**, 412–417.

Duval, M., Bahain, J. -J., Falguères, C., Garcia, J., Guilarte, V., Grün, R., Martínez, K., Moreno, D., Shao, Q., and Voinchet, P., 2015. Revisiting the ESR chronology of the early pleistocene hominin occupation at Vallparadís (Barcelona, Spain). *Quaternary International*. doi:10.1016/j.quaint.2014.08.054

Falguères, C., 2003. ESR dating and the human evolution: contribution to the chronology of the earliest humans in Europe. *Quaternary Science Reviews*, **22**(10–13), 1345–1351.

Falguères, C., Bahain, J.-J., Duval, M., Shao, Q., Han, F., Lebon, M., Mercier, N., Perez-Gonzalez, A., Dolo, J.-M., and Garcia, T., 2010. A 300–600 ka ESR/U-series chronology of Acheulian sites in Western Europe. *Quaternary International*, **223–224**, 293–298.

Fattibene, P., and Callens, F., 2010. EPR dosimetry with tooth enamel: a review. *Applied Radiation and Isotopes*, **68**(11), 2033–2116.

Goldstein, S. J., and Stirling, C. H., 2003. Techniques for measuring Uranium-series nuclides: 1992–2002. In. Bourdon, B., Henderson, G. M., Lundstrom, C. C., and Turner, S. P. (eds.), *Uranium-Series Geochemistry. Reviews in Mineralogy and Geochemistry.* Washington:Mineralogical Society of America, 52(1): 23–58.

Grün, R., 1989. Electron spin resonance (ESR) dating. *Quaternary International*, **1**, 65–109.

Grün, R., 1992. Suggestions for minimum requirements for reporting ESR age estimates. *Ancient TL*, **10**(3), 37–41.

Grün, R., 2007. Electron spin resonance dating. In Elias, S. A. (ed.), *Encyclopedia of Quaternary Science*. Amsterdam: Elsevier, pp. 1505–1516.

Grün, R., 2009a. The relevance of parametric U-uptake models in ESR age calculations. *Radiation Measurements*, **44**(5–6), 472–476.

Grün, R., 2009b. The DATA program for the calculation of ESR age estimates on tooth enamel. *Quaternary Geochronology*, **4**(3), 231–232.

Grün, R., Maroto, J., Eggins, S., Stringer, C., Robertson, S., Taylor, L., Mortimer, G., and McCulloch, M., 2006. ESR and U-series analyses of enamel and dentine fragments of the Banyoles mandible. *Journal of Human Evolution*, **50**(3), 347–358.

Grün, R., Aubert, M., Hellstrom, J., and Duval, M., 2010. The challenge of direct dating old human fossils. *Quaternary International*, **223–224**, 87–93.

Guérin, G., Mercier, N., and Adamiec, G., 2011. Dose-rate conversion factors: update. *Ancient TL*, **29**(1), 5–8.

Ikeya, M., 1975. Dating a stalactite by electron paramagnetic resonance. *Nature*, **255**(5503), 48–50.

Ikeya, M., 1993. *New Applications of Electron Spin Resonance: Dating, Dosimetry and Microscopy*. Singapore: World Scientific Publishing.

Laurent, M., Falguères, C., Bahain, J.-J., Rousseau, L., and Van Vliet Lanoé, B., 1998. ESR dating of quartz extracted from quaternary and neogene sediments: method, potential and actual limits. *Quaternary Geochronology*, **17**(11), 1057–1062.

Lin, M., Yin, G., Ding, Y., Cui, Y., Chen, K., Wu, C., and Xu, L., 2006. Reliability study on ESR dating of the aluminum center in quartz. *Radiation Measurements*, **41**(7–8), 1045–1049.

Ludwig, K. R., and Renne, P. R., 2000. Geochronology on the paleoanthropological time scale. *Evolutionary Anthropology: Issues, News, and Reviews*, **9**(2), 101–110.

Miallier, D., Guérin, G., Mercier, N., Pilleyre, T., and Sanzelle, S., 2009. The Clermont radiometric reference rocks: a convenient tool for dosimetric purposes. *Ancient TL*, **27**(2), 37–43.

Mishra, S., White, M. J., Beaumont, P., Antoine, P., Bridgland, D. R., Limondin-Lozouet, N., Santisteban, J. I., Schreve, D. C., Shaw, A. D., Wenban-Smith, F. F., Westaway, R. W. C., and White, T. S., 2007. Fluvial deposits as an archive of early human activity. *Quaternary Science Reviews*, **26**(22–24), 2996–3016.

Molodkov, A., 2001. ESR dating evidence for early man at a Lower Palaeolithic cave-site in the Northern Caucasus as derived from terrestrial mollusc shells. *Quaternary Science Reviews*, **20** (5–9), 1051–1055.

Monnier, J.-L., Hallégouët, B., Hinguant, S., Laurent, M., Auguste, P., Bahain, J.-J., Falguères, C., Gebhardt, A., Marguerie, D., Molines, N., Morzadec, H., and Yokoyama, Y., 1994. A new regional group of the Lower Palaeolithic in Brittany (France), recently dated by Electron Spin Resonance. *Comptes Rendus de lAcadémie des sciences de Paris*, **319**, 155–160.

Olley, J. M., Murray, A., and Roberts, R. G., 1996. The effects of disequilibria in the uranium and thorium decay chains on burial dose rates in fluvial sediments. *Quaternary Science Reviews*, **15**(7), 751–760.

Porat, N., and Schwarcz, H. P., 1991. Use of signal subtraction methods in ESR dating of burned flint. *International Journal of Radiation Applications and Instrumentation. Part D. Nuclear Tracks and Radiation Measurements*, **18**(1–2), 203–212.

Prescott, J. R., and Hutton, J. T., 1994. Cosmic ray contributions to dose rates for luminescence and ESR dating: large depths and long-term time variations. *Radiation Measurements*, **23**(2–3), 497–500.

Regulla, D. F., 2005. ESR spectrometry: a future-oriented tool for dosimetry and dating. *Applied Radiation and Isotopes*, **62**(2), 117–127.

Rink, W. J., 1997. Electron spin resonance (ESR) dating and ESR applications in quaternary science and archaeometry. *Radiation Measurements*, **27**(5–6), 975–1025.

Rink, W. J., Bartoll, J., Goldberg, P., and Ronen, A., 2003. ESR dating of archaeologically relevant authigenic terrestrial apatite veins from Tabun Cave, Israel. *Journal of Archaeological Science*, **30**(9), 1127–1138.

Romanyukha, A. A., Schauer, D. A., Thomas, J. A., and Regulla, D. F., 2005. Parameters affecting EPR dose reconstruction in teeth. *Applied Radiation and Isotopes*, **62**(2), 147–154.

Schwarcz, H. P., 1985. ESR studies of tooth enamel. *Nuclear Tracks and Radiation Measurements (1982)*, **10**(4–6), 865–867.

Shao, Q., Bahain, J.-J., Dolo, J.-M. and Falguères, C. (2014). Monte Carlo approach to calculate US-ESR age and age uncertainty for tooth enamel. *Quaternary Geochronology*, **22**, 99–106.

Torres, T. de, Ortiz, J. E., Grün, R., Eggins, S., Valladas, H., Mercier, N., Tisnérat-Laborde, N., Juliá, R., Soler, V., Martínez, E., Sánchez-Moral, S., Cañaveras, J. C., Lario, J., Badal, E., Lalueza-Fox, C., Rosas, A., Santamaría, D., de la Rasilla, M., and Fortea, J., 2010. Dating of the hominid (*Homo neanderthalensis*) remains accumulation from el Sidrón cave (Piloña, Asturias, North Spain): an example of a multi-methodological approach to the dating of upper Pleistocene sites. *Archaeometry*, **52**(4), 680–705.

Toyoda, S., and Ikeya, M., 1991. Thermal stabilities of paramagnetic defect and impurity centers in quartz: basis for ESR dating of thermal history. *Geochemical Journal*, **25**(6), 437–445.

Valladas, H., Mercier, N., Ayliffe, L. K., Falguères, C., Bahain, J.-J., Dolo, J.-M., Froget, L., Joron, J.-L., Masaoudi, H., Reyss, J.-L., and Moncel, M.-H., 2008. Radiometric dates for the Middle Palaeolithic sequence of Payre (Ardèche, France). *Quaternary Geochronology*, **3**(4), 377–389.

Voinchet, P., Falguères, C., Tissoux, H., Bahain, J.-J., Despriée, J., and Pirouelle, F., 2007. ESR dating of fluvial quartz: estimate of the minimal distance transport required for getting a maximum optical bleaching. *Quaternary Geochronology*, **2** (1–4), 363–366.

Voinchet, P., Despriée, J., Tissoux, H., Falguères, C., Bahain, J.-J., Gageonnet, R., Dépont, J., and Dolo, J.-M., 2010. ESR chronology of alluvial deposits and first human settlements of the Middle Loire Basin (Region Centre, France). *Quaternary Geochronology*, **5**(2–3), 381–384.

Yokoyama, Y., Bibron, R., and Falguères, C., 1988. Datation absolue des planchers stalagmitiques de la grotte du Vallonnet à Roquebrune-Cap-Martin (Alpes-Maritimes) France, par la Résonance de Spin Électronique (ESR). *L'Anthropologie*, **92**(2), 429–436.

Cross-references

$^{40}Ar/^{39}Ar$ and K–Ar Geochronology
Atapuerca
Inductively Coupled Plasma-Mass Spectrometry (ICP-MS)
Optically Stimulated Luminescence (OSL) Dating
Paleomagnetism
Speleothems
U-Series Dating

EOLIAN SETTINGS: LOESS

Marcelo A. Zárate
INCITAP (Institute of Earth and Environmental Sciences of La Pampa), CONICET/National University of La Pampa, Santa Rosa, La Pampa, Argentina

Definition

The term loess comes from the German word *Löss*, meaning loose, which is reported to have been first used to describe friable, silty deposits along the Rhine Valley near Heidelberg (Pye, 1995). Loess is a fine-grained sedimentary material resulting from the deposition of eolian dust, which extensively accumulated in some areas of the world during the Quaternary; it is also recorded in older geologic intervals (e.g., Soreghan et al., 2008). Loess is defined as a sediment composed predominantly of silt-sized particles (50–2 μm) with subordinated amounts of clay (<2 μm) and sand (>50 μm) that has been entrained, transported, and accumulated by the wind (Muhs, 2007). A more restrictive definition of loess, still regarded by some researchers, considers that loess is not simply eolian dust but the result of weathering and soil formation, a process called loessification (Pécsi, 1990; Smalley et al., 2011). If primary loess has been modified by weathering, soil formation, and diagenesis, it is called "weathered loess," while "reworked loess" has been eroded and redeposited by fluvial and/or slope processes. The term "loess-like deposit" refers to sediments with lithological properties similar to loess that have been transported by fluvial, lacustrine, or mass movement processes (Pye, 1987, 1995).

Geographical distribution

Loess and loess-like deposits cover approximately 10 % of the world (Pye, 1987; Pécsi, 1990). In the northern hemisphere, loess is extensive across the North American Great Plains, the northwestern USA, and Alaska (Figure 1a–c) (Roberts et al., 2007), Europe (northwestern France, south central Europe, Ukraine, Russia) (Rousseau et al., 2007), Central Asia (Tadjikistan, Uzbekistan, Kazakhstan, Yakutia, the Lake Baikal area) (Dodonov, 2007), and China (Figure 1h) (Porter, 2007). Geographically limited areas of loess deposits have been reported in Africa (Tunisia, Libya, Nigeria, and Namibia) and the Middle East (Figure 1i) (Israel, Yemen, and the UAE) (Coudé-Gaussen and Rognon, 1988; Brunotte et al., 2009; Crouvi et al., 2010). In the southern hemisphere, loess occurs over much of New Zealand, while loess and loess-like deposits are particularly extensive across the eastern Pampas (Figure 1d–g) and the Chaco Plain of Argentina along with areas of Bolivia, Paraguay, Brazil, and Uruguay (Zárate, 2007). Loess is mostly absent in Australia (Pye, 1987, 1995; Muhs, 2007).

Loess characteristics and composition

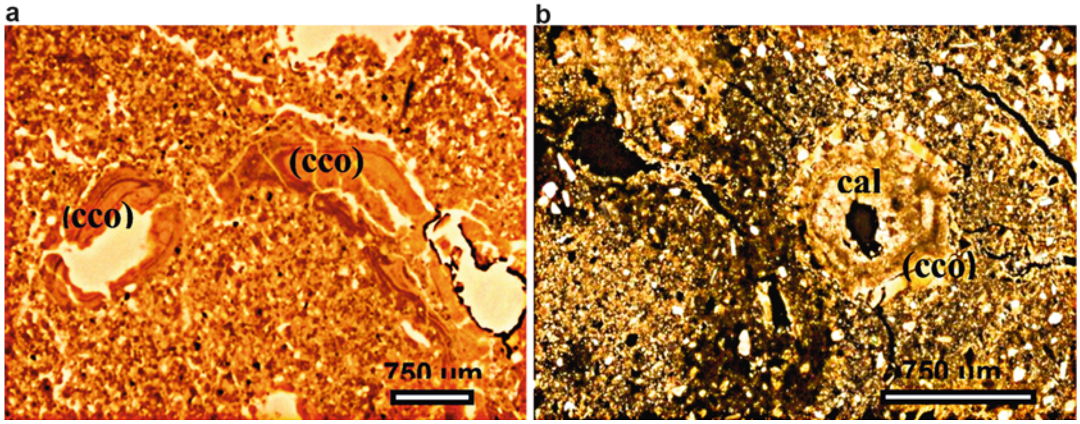
Loess is a friable and porous deposit of very variable thickness ranging from a few centimeters to hundreds of meters (Figure 1).

Usually unstratified or showing only a subtle structure, loess deposits exhibit a generally massive and homogeneous aspect (Figure 1a–e) (Pye, 1995; Smalley, 2004; Muhs, 2007). Although in general they are described as characteristically light yellowish or creamy brown calcareous deposits (Figure 1g), the color varies considerably, and loess is not always calcareous (calcareous nodules can be of either pedogenetic or groundwater origin). Secondary structures resulting from mammal (Figure 1f) and invertebrate activity are commonly present. Geotechnically, loess is characterized by high tensile strength resulting from interparticle bonding by clays and/or carbonates; the deposit is able to form vertical faces several meters high along natural or artificial exposures (Figure 1a, b, d); however, loess collapses if it is wetted or sheared (Derbyshire et al., 1994). Erodibility of loess

Eolian Settings: Loess, Figure 1 (**a**) Last Glacial age loess south of the Yukon River, central Alaska; (**b**) Bignell Hill, Nebraska, alternating sequence of Last Glacial (Peoria) loess, Brady paleosol, Holocene (Bignell) loess; (**c**) Last Glacial (Peoria) loess, southern (Mississippi) Mississippi River Valley (Photographs **a**, **b**, and **c**, courtesy of Daniel Muhs); (**d**) early to late Pleistocene loess/loess-like deposits with paleosol (15 m thick), northern Pampas, Buenos Aires, Argentina; (**e**) Last Glacial loess mantle and present soil, northern Pampas, Buenos Aires, Argentina; (**f**) loess section, *upper* part modified by present soil formation and burrows of fossorial rodents, a common bioturbation process in Pampean archaeological sites, southern Pampas, Buenos Aires, Argentina; (**g**) Last Glacial loess, upper ~1 m decalcified by pedogenesis, *lower* part (*whitish color* marked by **w**) unleached loess, northern Pampas, Buenos Aires, Argentina (Photos **d**, **e**, **f**, and **g** by Marcelo Zárate); (**h**) panoramic view of the ~200-m-thick Wuhan loess-paleosol section near Xian, China – paleosols are the darker layers (Photograph courtesy of the Chinese Academy of Sciences); (**i**) primary loess on top of a mountain summit (Mt. Harif) in central-western Negev (Photograph courtesy of Onn Crouvi).

deposits is usually very high, and severe soil erosion affects many of the loess areas of the world; the Chinese loess plateau is one of the most seriously eroded (e.g., Xinbao et al., 1990).

Loess stratigraphic sections are characterized by the occurrence of paleosols that record intervals of landscape stability, during which rates of loess accumulation and erosion were very low. During these intervals, soil-



Eolian Settings: Loess, Figure 2 Photomicrographs of thin sections from Pleistocene loess and loess-like deposits modified by pedogenesis, northern Pampas of Buenos Aires, Argentina (Gorina locality): (**a**) clay coatings (*cco*) around channels; (**b**) calcitic coating (*cal*) postdating (accumulating on top of) a clay coating (*cco*) (Photographs by Rob Kemp).

forming processes prevailed, and over several such cycles, noteworthy loess-paleosol sequences were produced (Figure 1b, d, h). Following the approach of soil micromorphology, the analysis of loess thin sections provides detailed insights into diagenetic changes and the interaction between sedimentation and pedogenesis during and after loess accumulation (Figure 2) (e.g., Kemp et al., 1995, 2006). The paleontological record of loess deposits may consist of fossil mammal remains and mollusk shells that are powerful paleoenvironmental and paleoclimatic indicators (Rousseau et al., 2007; Li et al., 2008). In addition, the analysis of recovered pollen and phytoliths provides information on the vegetation cover during loess accumulation and intervals of soil formation (e.g., Blinnikov et al., 2002; Komar et al., 2009). Commonly interstratified with eolian dust and paleosol sequences are tephra layers as well as non-eolian silty sediments (e.g., alluvium, colluvium, and mass movement deposits) that may include reworked loess (Mücher and Vreeken, 1981; Huang et al., 2006). Loess deposition can be dated by optical dating (Stevens et al., 2007; Roberts, 2008; Fuchs et al., 2013). Indirectly, chronology can be calibrated by means of magnetostratigraphy along with amino acid racemization on mollusk shells (e.g., Oches and McCoy, 1995).

The mineralogical composition of North American and Eurasian loess includes a prevailing amount of quartz, on the average 60–70 %, with a subordinated fraction of plagioclase, K-feldspar, mica, calcite, and small amounts of heavy minerals; illite and montmorillonite dominate among the clay minerals (Muhs, 2007; Smalley et al., 2011). The Argentine Pampean loess (Figure 2) is of volcaniclastic composition, with a dominant fraction of volcanic shards, volcanic lithic fragments, and lesser amounts of quartz grains (Zárate, 2007). Due to its characteristics and mineralogical composition, loess and loess soils have been the raw material for manufacturing ceramics, with examples reported from northern China since the early Neolithic (Needham et al., 2004), Europe (Vandiver et al., 1989), Israel (e.g., Goren, 1995), and Argentina (Frère et al., 2012).

Origin and source areas of loess particles

Two genetic models have been proposed to explain the origin of loess particles. The glacial loess model classically considered that silt size particles are produced by glacial grinding of crystalline rocks deposited in till that are later reworked by fluvial processes as outwash and finally entrained, transported, and deposited by wind (Muhs, 2013). In the desert loess model – for example, the loess of Israel (Figure 1i) – particles are the result of physical and chemical weathering, eolian abrasion, and ballistic impacts in dune fields (e.g., Crouvi et al., 2010; Muhs, 2013). The source areas of the particles forming loess deposits can be any of several environments characterized by high availability of sediments potentially deflated by the wind. They could be formerly extensive glacial outwash plains, floodplains of ephemeral streams in desert areas, dry lake and playa sediments, alluvial fans, stony desert surfaces, and weathered rock sections in formerly extensive deserts (Pye, 1995; Smalley, 2004; Muhs, 2007).

Geomorphological distribution

Loess geomorphology is an important source of information in geoarchaeology, as, for instance, in the search for archaeological sites, the geographical distribution of sedimentary settings, and paleolandscapes. Loess forms a blanket of variable thickness over preexisting landscapes and covers a wide range of landforms (e.g., fluvial terraces, moraines, alluvial fan surfaces, interfluvial areas) contributing also to the filling of rock-shelters and caves (Figure 3a, b) (Zárate and Flegenheimer, 1991; Woodward and Bailey, 2000; Cremaschi and Negrino, 2005).

Eolian Settings: Loess, Figure 3 Tandilia ranges of Buenos Aires, Argentina: (**a**) quartzitic rock-shelter Sierra Larga with loess mantle in the foreground modified by pedogenesis; (**b**) loess filling (70 cm) of rock-shelter modified by pedogenesis (*arrow* indicates archaeological level); (**c**) thin loess layer covering the quartzitic surface of a butte (Cerro El Sombrero) (the deposit that contains archaeological lithic remains is modified by present soil formation); (**d**) detailed view of a section of the pedogenized loess layer (a soil horizon) with a stem of a Fishtail projectile point (Photographs **c** and **d** courtesy of Nora Flegenheimer).

In geomorphological settings such as plains, loess forms mantles of relatively uniform thickness and low relief (Figure 1e). In contrast, on steep slopes, loess mantles may be thin, with increasing thickness in the downslope direction. The potential preservation of archaeological remains will vary according to the geomorphological setting of the loess deposit. Holding other controlling factors constant, a very low gradient landform (e.g., terrace tread, flat interfluvial surface) will be more stable than a hillslope setting, which is more subject to fluvial or mass movement processes, erosion, and the potential reworking and redeposition of archaeological remains embedded in the former loess deposit. In addition, the pattern of loess distribution, particularly in desert margin settings, is controlled by the extension and development of the vegetation cover that generally plays an important role in trapping eolian dust (Pye, 1995). Loess can bury partially or completely a ground surface and then smooth and mask previous topographies. In this respect, the landscape history of a loess area contributes to the interpretation of the archaeological record (e.g., Waters and Kuehn, 1996).

Loess-paleosol sequences and paleoclimatic significance

Loess-paleosol sequences are an excellent source of information in archaeological research. They constitute archives of past climatic and environmental conditions during intervals of human occupations and provide a valuable framework to analyze the stratigraphy and chronostratigraphy of archaeological records. During the Quaternary, loess was predominantly deposited during periods of cold and relatively dry conditions (Bordes, 1954; Kukla, 1977; Juvigne et al., 1996; Haesaerts and Mestdagh, 2000; van der Plicht et al., 2003; Fuchs et al., 2013) corresponding to glacial intervals, while paleosols formed under more humid and warmer conditions, which correlate with interglacial or interstadial intervals. The alternation of loess and paleosols thus becomes a useful tool in climostratigraphy.

The Chinese loess-paleosol sequence (Figure 1h) spanning the last 2.6 Ma is the most complete Quaternary continental archive of paleoclimatic conditions (Porter, 2007) and shows a good correlation with deep-sea records (Ding et al., 1994). Lu et al. (2011)

have illustrated the significance of a Chinese loess-paleosol sequence as a source of stratigraphic and paleoenvironmental information in Paleolithic archaeology.

Site formation processes in loess

Archaeological sites in loess deposits are generally better preserved in comparison with other eolian settings, such as dune fields, since they represent low-energy sedimentary environments. In general, archaeological remains show a relatively higher visibility in loess as a result of its homogeneous aspect, which makes the occurrence of exotic remains more obvious in comparison with other non-eolian sedimentary settings (Figure 3c, d). Bone remains show fairly good preservation due to the general dominance of alkaline conditions (e.g., Händel et al., 2009). Groundwater table oscillation and perched water tables may potentially affect the preservation of different remains, a factor still not fully analyzed. Post-burial transformation will depend on the environmental conditions that prevail in the loess area under study; a wide range of turbation processes may disturb and alter the archaeological context.

The rate of loess accumulation after sites are abandoned is crucial because it will determine how fast the burial occurs. Periods of higher loess accumulation rates will favor a more rapid burial and better preservation (e.g., Händel et al., 2009). Conversely, if human occupation occurs when loess surfaces are stable and affected by pedogenesis, which means very low rates of loess accumulation and higher rates of soil formation, archaeological remains will be subject to more dispersal and poorer preservation. In addition, on a stable loess soil surface, several successive occupations will be mixed, disturbed, and altered by pedoturbation, faunalturbation (Johnson, 2002), and also repetitive human occupations, resulting in the formation of palimpsests (cf. Ferring, 1986). The resulting archaeological layer will be composed of material from different occupation events that are not stratigraphically separated.

Loess and early agriculture

Loess is the parent material of very productive agricultural soils due to its particle size distribution, workability, mineralogical composition, good drainage conditions, soil aeration, and extensive penetration by roots. Loess soils yield nutrients such as K and N, which are of key importance for cereal growth without the need to add fertilizers (Catt, 2001). As a result, the inherent fertility of loess soils has played a crucial role in the development of Neolithic farming and agriculture in Europe (Bakels, 2009) and China (Ho, 1969). Renfrew and Bahn (2004) estimated that at least 70 % of the Linearbandkeramik (LBK) Culture sites of central and western Europe are found on loess areas.

Summary

Loess is a fine-grained eolian deposit that usually alternates with paleosols and covers wide areas of the northern hemisphere and to a lesser degree the southern hemisphere. Loess-paleosol sequences represent powerful archaeological tools that can help to reconstruct paleoclimatic and paleoenvironmental conditions, providing stratigraphic and chronostratigraphic context for archaeological sites. Loess settings are low-energy sedimentary environments favoring the preservation of archaeological remains in comparison with other settings. Site formation processes are mainly controlled by the balance between active loess sedimentation and soil formation along with the environmental and geomorphological conditions of the loess area.

Bibliography

Bakels, C. C., 2009. *The Western European Loess Belt: Agrarian History, 5300 BC–AD 1000*. Dordrecht: Springer.

Blinnikov, M., Busacca, A., and Whitlock, C., 2002. Reconstruction of the late Pleistocene grassland of the Columbia basin, Washington, USA, based on phytolith records in loess. *Palaeogeography Palaeoclimatology Palaeoecology*, **177** (1–2), 77–101.

Bordes, F., 1954. *Les limons quaternaires du Bassin de la Seine, stratigraphie et archéologie paléolithique*. Paris: Masson.

Brunotte, E., Maurer, B., Fischer, P., Lomax, J., and Sander, H., 2009. A sequence of fluvial and aeolian deposits (desert loess) and palaeosoils covering the last 60 ka in the Opuwo basin (Kaokoland/Kunene Region, Namibia) based on luminescence dating. *Quaternary International*, **196**(1–2), 71–85.

Catt, J. A., 2001. The agricultural importance of loess. *Earth-Science Reviews*, **54**(1–3), 213–229.

Coudé-Gaussen, G., and Rognon, P., 1988. The upper Pleistocene loess of southern Tunisia: a statement. *Earth Surface Processes and Landforms*, **13**(2), 137–151.

Cremaschi, M., and Negrino, F., 2005. Evidence for an abrupt climatic change at 8700 ^{14}C yr B.P. in rockshelters and caves of Gebel Qara (Dhofar-Oman): palaeoenvironmental implications. *Geoarchaeology*, **20**(6), 559–579.

Crouvi, O., Amit, R., Enzel, Y., and Gillespie, A. R., 2010. Active sand seas and the formation of desert loess. *Quaternary Science Reviews*, **29**(17–18), 2087–2098.

Derbyshire, E., Dijkstra, T. A., Smalley, I. J., and Li, Y., 1994. Failure mechanisms in loess and the effects of moisture content changes on remoulded strength. *Quaternary International*, **24**, 5–15.

Ding, Z., Yu, Z., Rutter, N. W., and Liu, T., 1994. Towards an orbital time scale for Chinese loess deposits. *Quaternary Science Reviews*, **13**(1), 39–70.

Dodonov, A. E., 2007. Loess records: central Asia. In Elias, S. A. (ed.), *Encyclopedia of Quaternary Science*. Amsterdam: Elsevier, pp. 1418–1429.

Ferring, C. R., 1986. Rates of fluvial sedimentation: implications for archaeological variability. *Geoarchaeology*, **1**(3), 259–274.

Frère, M. M., González, M. I., Chan, D., and Flores, M., 2012. Petrography of the archaeological pottery of the Salado River (Province of Buenos Aires, Argentina). *Comechingonia Revista de Arqueología*, **16**(2), 115–137.

Fuchs, M., Kreutzer, S., Rousseau, D.-D., Antoine, P., Hatté, C., Lagroix, F., Moine, O., Gauthier, C., Svoboda, J., and Lisá, L., 2013. The loess sequence of Dolní Věstonice, Czech Republic:

a new OSL-based chronology of the last climatic cycle. *Boreas*, **42**(3), 664–677.
Goren, Y., 1995. Shrines and ceramics in Chalcolithic Israel: the view through the petrographic microscope. *Archaeometry*, **37**(2), 287–305.
Haesaerts, P., and Mestdagh, H., 2000. Pedosedimentary evolution of the last interglacial and early glacial sequence in the European loess belt from Belgium to central Russia. *Geologie en Mijnbouw Netherlands Journal of Geosciences*, **79**(2–3), 313–324.
Händel, M., Simon, U., Einwögerer, T., and Neugebauer-Maresch, C., 2009. Loess deposits and the conservation of the archaeological record – the Krems-Wachtberg example. *Quaternary International*, **198**(1–2), 46–50.
Ho, P.-T., 1969. The loess and the origin of Chinese agriculture. *The American Historical Review*, **75**, 1–36.
Huang, C. C., Jia, Y., Pang, J., Zha, X., and Su, H., 2006. Holocene colluviation and its implications for tracing human-induced soil erosion and redeposition on the piedmont loess lands of the Qinling Mountains, northern China. *Geoderma*, **136**(3–4), 838–851.
Johnson, D. L., 2002. Darwin would be proud: bioturbation, dynamic denudation, and the power of theory in science. *Geoarchaeology*, **17**(1), 7–40.
Juvigne, E., Haesaerts, P., Mestdagh, H., Pissart, A., and Balescu, S., 1996. Revision du stratotype loessique de Kesselt (Limbourg, Belgique) – revision of the loess stratotype of Kesselt, Limbourg, Belgium. *Comptes Rendus de l'Academie des Sciences - Series IIa: Sciences de la Terre et des Planètes*, **323**(9), 801–807.
Kemp, R. A., Derbyshire, E., Xingmin, M., Fahu, C., and Baotian, P., 1995. Pedosedimentary reconstruction of a thick loess-paleosol sequence near Lanzhou in north-central China. *Quaternary Research*, **43**(1), 30–45.
Kemp, R. A., Zárate, M., Toms, P., King, M., Sanabria, J., and Argüello, G., 2006. Late Quaternary paleosols, stratigraphy and landscape evolution in the Northern Pampa, Argentina. *Quaternary Research*, **66**(1), 119–132.
Komar, M., Łanczont, M., and Madeyska, T., 2009. Spatial vegetation patterns based on palynological records in the loess area between the Dnieper and Odra Rivers during the last interglacial-glacial cycle. *Quaternary International*, **198**(1–2), 152–172.
Kukla, G. J., 1977. Pleistocene land-sea correlations 1. Europe. *Earth-Science Reviews*, **13**(4), 307–374.
Li, F., Rousseau, D.-D., Wu, N., Hao, Q., and Pei, Y., 2008. Late neogene evolution of the east Asian monsoon revealed by terrestrial mollusk record in Western Chinese loess plateau: from winter to summer dominated sub-regime. *Earth and Planetary Science Letters*, **274**(3–4), 439–447.
Lu, H., Sun, X., Wang, S., Cosgrove, R., Zhang, H., Yi, S., Ma, X., Wei, M., and Yang, Z., 2011. Ages for hominin occupation in Lushi basin, middle of South Luo River, central China. *Journal of Human Evolution*, **60**(5), 612–617.
Mücher, H. J., and Vreeken, W. J., 1981. (Re)deposition of loess in southern Limbourg, The Netherlands. 2. Micromorphology of the lower silt loam complex and comparison with deposits produced under laboratory conditions. *Earth Surface Processes and Landforms*, **6**(3–4), 355–363.
Muhs, D. R., 2007. Loess deposits, origins, and properties. In Elias, S. A. (ed.), *Encyclopedia of Quaternary Science*. Amsterdam: Elsevier, pp. 1405–1418.
Muhs, D. R., 2013. Loess and its geomorphic, stratigraphic, and paleoclimatic significance in the quaternary. In Shroder, J., Lancaster, N., Sherman, D. J., and Baas, A. C. W. (eds.), *Treatise on Geomorphology*. San Diego: Academic. Aeolian Geomorphology, Vol. 11, pp. 149–183.
Needham, J., Wood, N., and Kerr, R., 2004. *Science and Civilisation in China. volume 5, Part 12: Chemistry and Chemical Technology. Ceramic Technology*. Cambridge: Cambridge University Press.
Oches, E. A., and McCoy, W. D., 1995. Amino acid geochronology applied to the correlation and dating of Central European loess deposits. *Quaternary Science Reviews*, **14**(7–8), 767–782.
Pécsi, M., 1990. Loess is not just the accumulation of dust. *Quaternary International*, **7–8**, 7–21.
Porter, S. C., 2007. Loess records: China. In Elias, S. A. (ed.), *Encyclopedia of Quaternary Science*. Amsterdam: Elsevier, pp. 1429–1440.
Pye, K., 1987. *Aeolian Dust and Dust Deposits*. London: Academic.
Pye, K., 1995. The nature, origin and accumulation of loess. *Quaternary Science Reviews*, **14**(7–8), 653–667.
Renfrew, C., and Bahn, P. G., 2004. *Archaeology: Theories, Methods and Practice*, 4th edn. London: Thames & Hudson.
Roberts, H. M., 2008. The development and application of luminescence dating to loess deposits: a perspective on the past, present and future. *Boreas*, **37**, 483–507.
Roberts, H. M., Muhs, D. R., and Bettis, E. A., III, 2007. Loess records: North America. In Elias, S. A. (ed.), *Encyclopedia of Quaternary Science*. Amsterdam: Elsevier, pp. 1456–1466.
Rousseau, D.-D., Derbyshire, E., Antoine, P., and Hatté, C., 2007. Loess records: Europe. In Elias, S. A. (ed.), *Encyclopedia of Quaternary Science*. Amsterdam: Elsevier, pp. 1440–1456.
Smalley, I. J., 2004. Loess. In Goudie, A. S. (ed.), *Encyclopedia of Geomorphology*. London: Routledge, pp. 626–628.
Smalley, I. J., Marković, S. B., and Svirčev, Z., 2011. Loess is [almost totally formed by] the accumulation of dust. *Quaternary International*, **240**(1–2), 4–11.
Soreghan, G. S., Soreghan, M. J., and Hamilton, M. A., 2008. Origin and significance of loess in late Paleozoic western Pangaea: a record of tropical cold? *Palaeogeography Palaeoclimatology Palaeoecology*, **268**(3–4), 234–259.
Stevens, T., Thomas, D. S. G., Armitage, S. J., Lunn, H. R., and Lu, H., 2007. Reinterpreting climate proxy records from late Quaternary Chinese loess: a detailed OSL investigation. *Earth-Science Reviews*, **80**(1–2), 111–136.
Van der Plicht, J., Koulakovska, L., Damblon, F., Chirica, V., Borziak, I., and Haesaerts, P., 2003. The East Carpathian loess record: a reference for the middle and late pleniglacial stratigraphy in central Europe [La séquence loessique du domaine est-carpatique: une référence pour le pléniglaciaire moyen et supérieur d'Europe centrale]. *Quaternaire*, **14**(3), 163–188.
Vandiver, P. B., Soffer, O., Klima, B., and Svoboda, J., 1989. The origins of ceramic technology at Dolni Věstonice, Czechoslovakia. *Science*, **246**(4933), 1002–1008.
Waters, M. R., and Kuehn, D. D., 1996. The geoarchaeology of place: the effect of geological processes on the preservation and interpretation of the archaeological record. *American Antiquity*, **61**(3), 483–497.
Woodward, J. C., and Bailey, G. N., 2000. Sediment sources and terminal Pleistocene geomorphological processes recorded in rockshelter sequences in northwest Greece. In Foster, I. - D. L. (ed.), *Tracers in Geomorphology*. Chichester: Wiley, pp. 521–551.
Xinbao, Z., Higgitt, D. L., and Wallen, D. E., 1990. A preliminary assessment of the potential for using caesium-137 to estimate rates of soil erosion in the Loess Plateau of China. *Hydrological Sciences Journal*, **35**(3), 243–252.
Zárate, M., 2007. Loess records: south America. In Elias, S. A. (ed.), *Encyclopedia of Quaternary Science*. Amsterdam: Elsevier, pp. 1466–1479.
Zárate, M., and Flegenheimer, N., 1991. Geoarchaeology of the Cerro La China locality (Buenos Aires, Argentina): site 2 and site 3. *Geoarchaeology*, **6**(3), 273–294.

Cross-references

Amino Acid Racemization
Chronostratigraphy
Eolian Settings: Sand
Geomorphology
Loessic Paleolithic, Tajikistan
Magnetometry for Archaeology
Optically Stimulated Luminescence (OSL) Dating
Radiocarbon Dating
Soil Micromorphology
Soils
Stratigraphy

EOLIAN SETTINGS: SAND

Andrew S. Goudie
School of Geography and the Environment, University of Oxford, Oxford, UK

Definition

Dunes and other sand depositional settings.

Introduction

Large numbers of important archaeological sites have been identified in areas with sand dunes and eolian sand deposits: on ocean coasts (Erlandson et al., 2005; Winterbottom and Dawson, 2005; Anderson et al., 2006) where middens are often abundant, on lake shores such as those of Lake Michigan (Lovis et al., 2012), and in the world's dry lands (which will be the main focus of this entry). Dunes provide an environment of accumulation in which (1) artifacts may be preserved (e.g., Fuchs et al., 2008); (2) indications of former climatic and other environmental conditions may be buried in temporal sequences, such as paleosols (Butzer, 2004) and phytoliths (Boyd, 2005); (3) lake deposits (Parker and Goudie, 2008), fluvial gravels (Atkinson et al., 2013), and other indicators of humidity may be interspersed within the sand; and (4) strata or levels within the accumulation may be susceptible to dating by techniques such as optical dating, including OSL (optically stimulated luminescence). There may, however, be problems of artifact displacement in dune situations (Rick, 2002; Mayer, 2003).

Dune types

There is now a huge literature on dunes and various excellent recent texts, including those by Lancaster (1995) and Warren (2013). Good introductions to the physics of sand movement are provided by Sherman and Li (2012), but the classic work remains that by Bagnold (1941).

Dune forms are diverse and vary between and across dune fields. Moreover, one form may be superimposed upon another. Many classification schemes for dune morphology have been developed, and it is recognized that there are a number of possible controls on the development of different dune types in different areas. Factors include the amount and grain size of available sand (Eastwood et al., 2011), the transport capacity and directional variability of wind (Fryberger and Dean, 1979), the vegetation cover, the evolutionary stage that the dunes have reached, the presence of bedrock highs, the position of the dunes within a sand sea, whether or not sand budgets are positive or negative (Mainguet and Chemin, 1990), the presence of high groundwater levels (which may favor the formation of parabolic forms), and the areal extent of the dune field.

There are, however, some basic dune types that have widespread expression in many of the world's deserts. Tsoar et al. (2004) proposed a threefold classification: *migrating* dunes (exemplified by transverse forms, such as barchans), *elongating* dunes (exemplified by linear dunes), and *accumulating* dunes (exemplified by star dunes).

In addition to these free forms, there are also dunes that are fixed or anchored in the landscape by topographic features or vegetation. Some of these features have been called *sand ramps*, which are sloping sand forms blown against the front of elevated terrain and within which multiple generations built up over time can be identified. They often are contaminated by talus, stone horizons, and colluvium derived from the slopes which they abut, and they may contain paleosols (Bateman et al., 2012), thus making them excellent repositories of climate and local environmental information.

Another type of topographic dune is the lunette: a roughly crescentic eolian accumulation that occurs on the downwind margins of closed basins (pans) (Figure 1). They may be several kilometers long and may attain heights in excess of 60 m in exceptional cases. They tend to occur in areas where present-day precipitation levels are between about 100 and 700 mm, but their stratigraphy can yield good indications of past changes in climate and hydrological conditions (Lawson and Thomas, 2002). They are also landforms within which archaeological sites may occur, as in the Willandra Lakes of Australia (Fitzsimmons et al., 2014) and the High Plains of the USA (Rich, 2013).

Lunettes may accumulate rapidly, with rates in the Kalahari reaching 10 m in 1,000 years (Telfer and Thomas, 2006), and some basins may have multiple lunettes on their lee sides (Harper and Gilkes, 2004). Various hypotheses have been put forward to explain differences in lunette composition. Campbell (1968) believed that deflation from a lake bed could account for many lunette features; however, she also recognized that some of the material could be derived from wave-generated beaches and so could be analogous to primary coastal foredunes. This concept was developed for Lake Mungo by Bowler (1973), who saw sandy lunette facies as being associated with a beach provenance at times of relatively high water levels, whereas clay and evaporite-rich facies formed during drier phases when deflation of the desiccated lake floor was possible.

Eolian Settings: Sand, Figure 1 A major lunette dune from Kelbia, Tunisia. The salt lake from which it is derived is visible in the background.

Parabolic dunes occur in areas with vegetation cover and/or high groundwater levels. The importance of vegetation cover in areas with parabolic dunes, such as the Canadian prairies or the US High Plains, suggests that such factors as droughts and human disturbance may cause rapid changes of state to occur (Hugenholtz et al., 2010). Clear stratigraphic evidence indicates that parabolic dunes have undergone repeated phases of activity and stability at different points throughout the Holocene in response to cycles of drought (Forman et al., 2009).

One often finds that at any one location, different dune types may be superimposed upon each other, as the following examples show. In the Gran Desierto of Mexico, for example, Beveridge et al. (2006) found five different patterns dating to different ages. The oldest pattern consisted of linear dunes believed to have formed between 26 and 12 ka. This was followed by the construction of three sequential phases of crescentic dunes. Finally, in the last few thousands of years, star dunes and a sand sheet formed. These different patterns can be related to changes in aridity, wind direction, and sediment supply in the Late Quaternary. Equally, in the Algodones dune field of California, Derickson et al. (2008) found five dune types showing varying degrees of superimposition. In the northeastern Rub' al Khali in the United Arab Emirates, large linear dunes trend from approximately southwest to northeast, and they are overlain by much smaller linear ridges that trend from northwest to southeast (Atkinson et al., 2013). In the Badain Jaran Desert of China, Dong et al. (2009) identified three dune generations.

Dunes as paleoenvironmental indicators

The former extent of major tropical and subtropical sand seas (called ergs from the Arabic term for a dune field) gives an indication of former dry conditions. That some dunes are relict rather than active is indicated by deep weathering and intense iron-oxide staining, clay and humus development, silica or carbonate accumulation, stabilization by vegetation, gullying by fluvial action, and degradation to angles considerably below that of the angle of repose of sand – normally ca. 32–33° on lee slopes. Sometimes, archaeological evidence can be used to show that sand deposition is no longer progressing, while elsewhere dunes have been found to be flooded by lakes.

Sand movement will generally be restricted so long as there is good vegetation cover, though small parabolic dunes are probably more tolerant in this respect than the more massive linear dunes and barchans. Indeed, dunes can develop where there is limited vegetation cover, and vegetation may contribute to their development. Sediment availability is also an important factor in determining dune mobility. It is, therefore, difficult to provide very precise rainfall limits to dune development. Nevertheless, studies where dunes are currently moving and developing suggest that vegetation becomes effective in restricting dune movement only where annual precipitation totals exceed about 100–300 mm. These figures apply for warm, non-coastal areas. Fossil dunes typically occur in areas with 600–1,200 mm of mean annual rainfall (see Anderson et al., 2013; Table 4.1).

Eolian Settings: Sand, Figure 2 A series of dunes of different ages and colors that have accumulated in the Budha Pushkar basin, Rajasthan, India. Stone tools have been recovered from surfaces between the different dune types.

In India, fossil dunes have been identified in Gujarat and Rajasthan (Allchin et al., 1978) where they have been sites of Paleolithic occupation (Blinkhorn, 2013) (Figure 2). They occupy zones where the annual rainfall is now as high as 750–900 mm.

In southern Africa, the Kalahari is dominantly a fossil desert, now covered by a dense mixture of woodland, grassland, and shrubs. Relict dunes are widespread in Botswana, Angola, Zimbabwe, and Zambia and may extend as far north as the Congo rainforest zone (Shaw and Goudie, 2002). North of the equator, fossil dune fields extend south into the savannah and forest of West Africa. The "Ancient Erg of Hausaland" (Grove, 1958) occurs where present rainfall is as high as 1,000 mm per annum. Further east, in the Sudan, a series of fixed dunes, called *Qoz*, extend as far south as 10° N lat. and merge northward, locally, with mobile dunes at about 16° N. lat. (Grove and Warren, 1968).

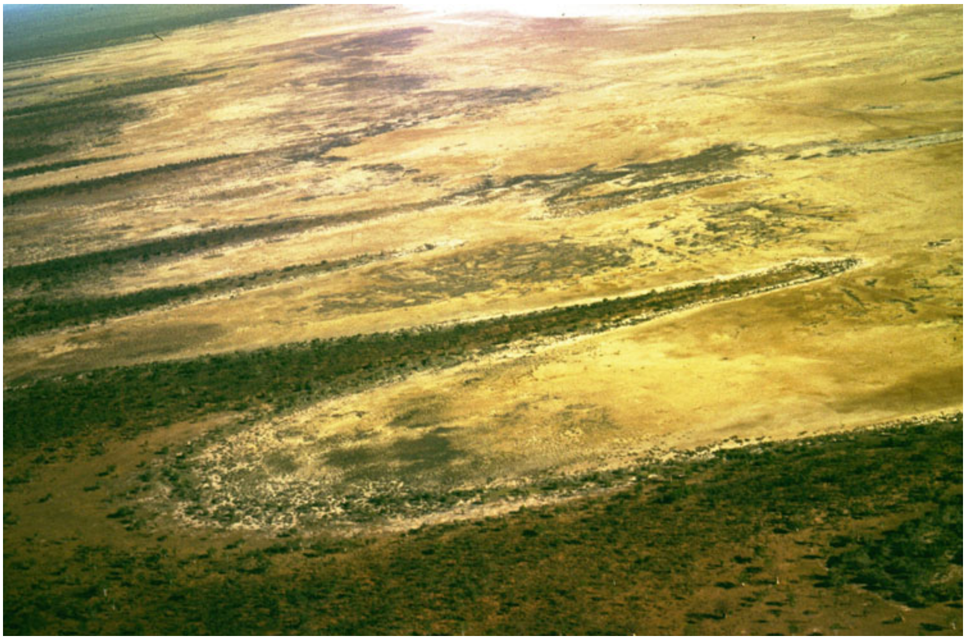
In the USA, parts of the High Plains were formerly covered by large dune fields. Substantial dune development took place in the Late Pleistocene and during the drier portions of the Holocene (Halfen et al., 2012). Relict Quaternary dunes also occur in South Carolina and elsewhere along the eastern seaboard of the USA (Swezey et al., 2013). The American dunes contain many important archaeological sites, and these are found from Texas in the south (e.g., Holliday, 2000, 2001; Hall et al., 2010) to Wyoming in the north (Mayer, 2002).

In South America, in the Llanos, fossil dunes underlying the Venezuelan savannah region extend southward as far as 5°20′ N lat. Other dunes occur in northern Amazonia and the Roraima-Guyana (Latrubesse and Nelson, 2001). Another erg was in the valley of the São Francisco in Bahia State, Brazil. In addition, it is likely that eolian activity was much more extensive in the Pantanal, the Pampas, and other parts of Argentina (Tripaldi and Forman, 2007), including the steppes of Tierra del Fuego (Coronato et al., 2011).

In Australia, fossil dunes are developed over wide areas (Wasson et al. 1988; Nanson et al., 1995). They occur from Tasmania (Sigleo and Colhoun, 1982) in the south to the Fitzroy plains of north Western Australia, where they pass under (and thus predate) the Holocene alluvium of King Sound (Jennings, 1975) (Figure 3). In the country to the south of the Barkly Tableland, they probably indicate a decrease of annual rainfall in that area to between 150 and 500 mm, indicating an equatorward shift of the isohyets by about 8° of latitude, or around 900 km. Lunette dunes on the lee sides of closed depressions have also had a lengthy history and provide many details about both dune and lake evolution (see, e.g., Chen et al., 1995), in addition to being sites where human remains and artifacts occur (Fitzsimmons et al. 2014), as at Lake Mungo.

Thus, as this brief review shows, large swathes of low latitudes possess dunes that currently have limited or negligible eolian activity (Telfer and Hesse, 2013). Although precipitation amounts may have been a major controlling factor in their former activity, there are other factors that must be considered, including changes in wind energy and sand supply (Chase, 2009; Roskin et al., 2011).

There is evidence that the strength of the trade winds may have intensified during particular phases of the



Eolian Settings: Sand, Figure 3 Relict linear dunes, of probable Late Pleistocene age, that were flooded by the postglacial rise of sea level in the King Sound area, near Derby, West Kimberley, Australia.

Pleistocene, causing increased eolian activity. Northeasterly trade wind velocities were higher during glacials, probably because of an intensified atmospheric circulation; this intensity was caused by the increased temperature gradient between the North Pole and the equator due to the presence of an extended Northern Hemisphere ice cap (Ruddiman, 1997; Broecker, 2002).

Sand supply is another major control influencing dune formation. In this connection, rivers may be an important source of sand, so that their state is important (Londoño et al., 2012). Broad, sandy channels that dry out seasonally may provide ample sand for dune construction, while perennially wet or deeply incised channels may provide little (Wright et al., 2011). It is also possible that, in some cases, increased fluvial sediment transport could have led to a much greater sand supply to river channels so that dune accretion may have been greater even if the climate was moister than today (Ellwein et al., 2011). In very arid areas, moist phases may have been required to create aggradation of fans and alluvial washes through increased erosion; with the onset of drier conditions, the accumulated sand could then be deflated, enabling dune accretion to occur (Lancaster and Mahan, 2012).

Sea-level changes may control the availability of sand supply in coastal environments as seems to have been the case in the lands bordering the Arabian/Persian Gulf and on the coast of the southern Levant. On one hand, at times of low sea level, large expanses of former seafloor would be dry land, making it a source of sand (Goring-Morris and Goldberg, 1990), while on the other, rising sea levels would comb up large quantities of material which could then be blown inland (Teller et al., 2000). Even the quite modest sea-level changes of the Holocene may have affected dune accumulation (Compton and Franceschini, 2005). Moreover, sea-level changes may also have influenced dunes through control of groundwater levels in near coastal environments (Carr et al., 2006).

Dating of sand dunes

The development of optically stimulated luminescence (OSL) dating has provided the means for determining dune ages, and there are now many dates for periods of dune accumulation (e.g., Fitzsimmons et al., 2012; Stone and Thomas, 2012) (Figure 4). When conditions are favorable for the application of such dating methods, results can yield ages in the hundreds of thousands of years. It is important to point out, however, that the dates are generally for periods of sand accumulation and stabilization rather than being for periods of actual dune movement during which the sand is repeatedly being exposed to light in the process of moving (Lu et al., 2011; Thomas, 2013). In many areas, dune activity appears to have been considerable in the period between the Last Glacial Maximum and the early Holocene wet phase.

There are numerous problems in interpreting OSL dates on dunes, including the fact that erosional phases may cause the record to be incomplete (Telfer et al., 2010), and bioturbation can lead to mixing and displacement (Bateman et al., 2007). Moreover, the record obtained from dunes in close proximity to each other may not always be the same, and as more and more dates are

Eolian Settings: Sand, Figure 4 Linear dunes in the United Arab Emirates being sampled for OSL dating after face clearance.

obtained from an area, some of the supposed intervals of non-accumulation of sand may turn out not to be as static as once thought. Equally, a more intensive vertical sampling strategy may have a similar outcome (Stone and Thomas, 2008).

Site formation processes in dunes

Although dunes can be a treasure house of archaeological materials embedded within them, care needs to be taken in their interpretation. For example, deflation of dunes may lead to preferential removal of fine materials, such as small fish bones, while other susceptible materials may be destroyed by eolian abrasion (Rick, 2002). Artifacts can also be vertically displaced as a result of post-occupational erosion and deflation (Mayer, 2002). In addition, bioturbation and other processes may lead to upward or downward movement of artifacts from their original level of deposition, and inverted clast stratigraphy has been reported (Buck et al., 2002).

Summary

Areas of eolian sand deposition have often proven to be the locations of major archaeological sites. In the last half century or so, many relict dunes have been identified in low- and mid-latitude locations, indicating by their presence former periods of aridity. We now recognize, however, that other factors may also have played a role, including changes in windiness, sand supply, and sea levels. Another important development has been the application of optical dating for establishing chronologies of dune accumulation. The presence of archaeological materials in dunes needs to be interpreted with care, because site formation processes may not be readily apparent, making accurate conclusions over their age and relationship with human exploitation challenging.

Bibliography

Allchin, B., Goudie, A. S., and Hegde, K. T. M., 1978. *The Prehistory and Palaeogeography of the Great Indian Desert*. London: Academic Press.

Anderson, A., Roberts, R., Dickinson, W., Clark, G., Burley, D., de Biran, A., Hope, G., and Nunn, P., 2006. Times of sand: sedimentary history and archaeology at the Sigatoka Dunes, Fiji. *Geoarchaeology*, **21**(2), 131–154.

Anderson, D. E., Goudie, A. S., and Parker, A. G., 2013. *Global Environments Through the Quaternary: Exploring Environmental Change*, 2nd edn. Oxford: Oxford University Press.

Atkinson, O. A. C., Thomas, D. S. G., Parker, A. G., and Goudie, A. S., 2013. Late Quaternary humidity and aridity dynamics in the northeast Rub' al-Khali, United Arab Emirates: implications for early human dispersal and occupation of eastern Arabia. *Quaternary International*, **300**, 292–301.

Bagnold, R. A., 1941. *The Physics of Blown Sand and Desert Dunes*. London: Methuen.

Bateman, M. D., Boulter, C. H., Carr, A. S., Frederick, C. D., Peter, D., and Wilder, M., 2007. Preserving the palaeoenvironmental record in drylands: bioturbation and its significance for luminescence-derived chronologies. *Sedimentary Geology*, **195** (1–2), 5–19.

Bateman, M. D., Bryant, R. G., Foster, I. D. L., Livingstone, I., and Parsons, A. J., 2012. On the formation of sand ramps: a case study from the Mojave Desert. *Geomorphology*, **161–162**, 93–109.

Beveridge, C., Kocurek, G., Ewing, R. C., Lancaster, N., Morthekai, P., Singhvi, A., and Mahan, S. A., 2006. Development of spatially diverse and complex dune-field patterns: Gran Desierto Dune Field, Sonora, Mexico. *Sedimentology*, **53**(6), 1391–1409.

Blinkhorn, J., 2013. A new synthesis of evidence for the Upper Pleistocene occupation of 16R dune and its southern Asian context. *Quaternary International*, **300**, 282–291.

Bowler, J. M., 1973. Clay dunes: their occurrence, formation and environmental significance. *Earth-Science Reviews*, **9**(4), 315–338.

Boyd, M., 2005. Phytoliths as paleoenvironmental indicators in a dune field on the northern Great Plains. *Journal of Arid Environments*, **61**(3), 357–375.

Broecker, W. S., 2002. Dust: climate's Rosetta Stone. *Proceedings of the American Philosophical Society*, **146**(1), 77–80.

Buck, B. J., Kipp, J., Jr., and Monger, H. C., 2002. Inverted clast stratigraphy in an eolian archaeological environment. *Geoarchaeology*, **17**(7), 665–687.

Butzer, K. W., 2004. Coastal eolian sands, paleosols, and Pleistocene geoarchaeology of the Southwestern Cape, South Africa. *Journal of Archaeological Science*, **31**(12), 1743–1781.

Campbell, E. M., 1968. Lunettes in South Australia. *Transactions of the Royal Society of South Australia*, **92**, 85–109.

Carr, A. S., Thomas, D. S. G., and Bateman, M. D., 2006. Climatic and sea level controls on Late Quaternary eolian activity on the

Agulhas Plain, South Africa. *Quaternary Research*, **65**(2), 252–263.
Chase, B., 2009. Evaluating the use of dune sediments as a proxy for palaeo-aridity: a southern African case study. *Earth-Science Reviews*, **93**(1–2), 31–45.
Chen, X. Y., Chappell, J., and Murray, A. S., 1995. High (ground) water levels and dune development in central Australia: TL dates from gypsum and quartz dunes around Lake Lewis (Napperby), Northern Territory. *Geomorphology*, **11**(4), 311–322.
Compton, J. S., and Franceschini, G., 2005. Holocene geoarchaeology of the sixteen mile beach barrier dunes in the Western Cape, South Africa. *Quaternary Research*, **63**(1), 99–107.
Coronato, A., Fanning, P., Salemme, M., Oría, J., Pickard, J., and Ponce, J. F., 2011. Aeolian sequence and the archaeological record in the Fuegian steppe, Argentina. *Quaternary International*, **245**(1), 122–135.
Derickson, D., Kocurek, G., Ewing, R. C., and Bristow, C., 2008. Origin of a complex and spatially diverse dune-field pattern, Algodones, southeastern California. *Geomorphology*, **99**(1–4), 186–204.
Dong, Z., Qian, G., Luo, W., Zhang, Z., Xiao, S., and Zhao, A., 2009. Geomorphological hierarchies for complex mega-dunes and their implications for mega-dune evolution in the Badain Jaran Desert. *Geomorphology*, **106**(3–4), 180–185.
Eastwood, E., Nield, J., Baas, A., and Kocurek, G., 2011. Modelling controls on aeolian dune-field pattern evolution. *Sedimentology*, **58**(6), 1391–1406.
Ellwein, A. L., Mahan, S. A., and McFadden, L. D., 2011. New optically stimulated luminescence ages provide evidence of MIS3 and MIS2 eolian activity on Black Mesa, northeastern Arizona, USA. *Quaternary Research*, **75**(3), 395–398.
Erlandson, J. M., Rick, T. C., and Peterson, C., 2005. A geoarchaeological chronology of Holocene dune building on San Miguel Island, California. *The Holocene*, **15**(8), 1227–1235.
Fitzsimmons, K. E., Miller, G. H., Spooner, N. A., and Magee, J. W., 2012. Aridity in the monsoon zone as indicated by desert dune formation in the Gregory Lakes basin, northwestern Australia. *Australian Journal of Earth Sciences*, **59**(4), 469–478.
Fitzsimmons, K. E., Stern, N., and Murray-Wallace, C. V., 2014. Depositional history and archaeology of the central Lake Mungo lunette, Willandra Lakes, southeast Australia. *Journal of Archaeological Science*, **41**, 349–364.
Forman, S. L., Nordt, L., Gomez, J., and Pierson, J., 2009. Late Holocene dune migration on the south Texas sand sheet. *Geomorphology*, **108**(3–4), 159–170.
Fryberger, S. G., with Dean, G., 1979. Dune forms and wind regime. In McKee, E. D. (ed.), *A Study of Global Sand Seas*. Washington, DC: US Government Printing Office. United States Geological Survey Professional Paper 1052, pp. 137–169.
Fuchs, M., Kandel, A. W., Conard, N. J., Walker, S. J., and Felix-Henningsen, P., 2008. Geoarchaeological and chronostratigraphical investigations of open-air sites in the Geelbek Dunes, South Africa. *Geoarchaeology*, **23**(4), 425–449.
Goring-Morris, A. N., and Goldberg, P., 1990. Late Quaternary dune incursions in the southern levant: archaeology, chronology and palaeoenvironments. *Quaternary International*, **5**, 115–137.
Grove, A. T., 1958. The ancient erg of Hausaland, and similar formations on the south side of the Sahara. *Geographical Journal*, **124**(4), 528–533.
Grove, A. T., and Warren, A., 1968. Quaternary landforms and climate on the south side of the Sahara. *Geographical Journal*, **134**(2), 194–208.
Halfen, A. F., Johnson, W. C., Hanson, P. R., Woodburn, T. L., Young, A. R., and Ludvigson, G. A., 2012. Activation history of the Hutchinson dunes in east-central Kansas, USA during the past 2200 years. *Aeolian Research*, **5**, 9–20.
Hall, S. A., Miller, M. R., and Goble, R. J., 2010. Geochronology of the Bolson sand sheet, New Mexico and Texas, and its archaeological significance. *Bulletin of the Geological Society of America*, **122**(11–12), 1950–1967.
Harper, R. J., and Gilkes, R. J., 2004. Aeolian influences on the soils and landforms of the southern Yilgarn Craton of semi-arid, southwestern Australia. *Geomorphology*, **59**(1–4), 215–235.
Holliday, V. T., 2000. Folsom drought and episodic drying on the Southern High Plains from 10,900–10,200 ^{14}C yr B.P. *Quaternary Research*, **53**(1), 1–12.
Holliday, V. T., 2001. Stratigraphy and geochronology of upper Quaternary eolian sand on the Southern High Plains of Texas and New Mexico, United States. *Bulletin of the Geological Society of America*, **113**(1), 88–108.
Hugenholtz, C. H., Bender, D., and Wolfe, S. A., 2010. Declining sand dune activity in the southern Canadian prairies: historical context, controls and ecosystem implications. *Aeolian Research*, **2**(2–3), 71–82.
Jennings, J. N., 1975. Desert dunes and estuarine fill in the Fitzroy estuary (North-Western Australia). *Catena*, **2**, 216–262.
Lancaster, N., 1995. *Geomorphology of Desert Dunes*. London: Routledge.
Lancaster, N., and Mahan, S. A., 2012. Holocene dune formation at Ash Meadows National Wildlife Area, Nevada, USA. *Quaternary Research*, **78**(2), 266–274.
Latrubesse, E. M., and Nelson, B. W., 2001. Evidence for Late Quaternary aeolian activity in the Roraima-Guyana Region. *Catena*, **43**(1), 63–80.
Lawson, M. P., and Thomas, D. S. G., 2002. Late Quaternary lunette dune sedimentation in the southwestern Kalahari Desert, South Africa: luminescence based chronologies of aeolian activity. *Quaternary Science Reviews*, **21**(7), 825–836.
Londoño, A. C., Forman, S. L., Eichler, T., and Pierson, J., 2012. Episodic eolian deposition in the past ca. 50,000 years in the Alto Ilo dune field, southern Peru. *Palaeogeography Palaeoclimatology Palaeoecology*, **346–347**, 12–24.
Lovis, W. A., Arbogast, A. F., and Monaghan, G. W., 2012. *The Geoarchaeology of Lake Michigan Coastal Dunes*. East Lansing: Michigan State University Press.
Lu, H., Mason, J. A., Stevens, T., Zhou, Y., Yi, S., and Miao, X., 2011. Response of surface processes to climatic change in the dunefields and Loess Plateau of North China during the late Quaternary. *Earth Surface Processes and Landforms*, **36**(12), 1590–1603.
Mainguet, M., and Chemin, M.-C., 1990. Le massif du Tibesti dans le système éolien du Sahara: Réflexion sur la génèse du Lac Tchad. *Berliner Geographische Studien*, **30**, 261–276.
Mayer, J. H., 2002. Evaluating natural site formation processes in eolian dune sands: a case study from the Krmpotich Folsom site, Killpecker Dunes, Wyoming. *Journal of Archaeological Science*, **29**(10), 1199–1211.
Mayer, J. H., 2003. Paleoindian geoarchaeology and paleoenvironments of the western Killpecker Dunes, Wyoming, U.S.A. *Geoarchaeology*, **18**(1), 35–69.
Nanson, G. C., Chen, X. Y., and Price, D. M., 1995. Aeolian and fluvial evidence of changing climate and wind patterns during the past 100 ka in the western Simpson Desert, Australia. *Palaeogeography Palaeoclimatology Palaeoecology*, **113**(1), 87–102.
Parker, A. G., and Goudie, A. S., 2008. Geomorphological and palaeoenvironmental investigations in the southeastern Arabian Gulf region and the implication for the archaeology of the region. *Geomorphology*, **101**(3), 458–470.
Rich, J., 2013. A 250,000-year record of lunette dune accumulation on the Southern High Plains, USA and implications for past climates. *Quaternary Science Reviews*, **62**, 1–20.

Rick, T. C., 2002. Eolian processes, ground cover, and the archaeology of coastal dunes: a taphonomic case study from San Miguel Island, California, U.S.A. *Geoarchaeology*, **17**(8), 811–833.

Roskin, J., Porat, N., Tsoar, H., Blumberg, D. G., and Zander, A. M., 2011. Age, origin and climatic controls on vegetated linear dunes in the northwestern Negev Desert (Israel). *Quaternary Science Reviews*, **30**(13–14), 1649–1674.

Ruddiman, W. F., 1997. Tropical Atlantic terrigenous fluxes since 25,000 yrs B.P. *Marine Geology*, **136**(3–4), 189–207.

Shaw, A. I., and Goudie, A. S., 2002. Geomorphological evidence for the extension of the Mega-Kalahari into south-central Angola. *South African Geographical Journal*, **84**(2), 182–194.

Sherman, D. J., and Li, B., 2012. Predicting aeolian sand transport rates: a reevaluation of models. *Aeolian Research*, **3**(4), 371–378.

Sigleo, W. R., and Colhoun, E. A., 1982. Terrestrial dunes, man and late Quaternary environment in southern Tasmania. *Palaeogeography Palaeoclimatology Palaeoecology*, **39**(1–2), 87–121.

Stone, A. E. C., and Thomas, D. S. G., 2008. Linear dune accumulation chronologies from the southwest Kalahari, Namibia: challenges of reconstructing late Quaternary palaeoenvironments from aeolian landforms. *Quaternary Science Reviews*, **27** (17–18), 1667–1681.

Stone, A. E. C., and Thomas, D. S. G., 2012. Casting new light on late Quaternary environmental and palaeohydrological change in the Namib Desert: a review of the application of optically stimulated luminescence in the region. *Journal of Arid Environments*, **93**, 40–58.

Swezey, C. S., Schultz, A. P., González, W. A., Bernhardt, C. E., Doar, W. R., III, Garrity, C. P., Mahan, S. A., and McGeehin, J. P., 2013. Quaternary eolian dunes in the Savannah River valley, Jasper County, South Carolina, USA. *Quaternary Research*, **80**(2), 250–264.

Telfer, M. W., and Hesse, P. P., 2013. Palaeoenvironmental reconstructions from linear dunefields: recent progress, current challenges and future directions. *Quaternary Science Reviews*, **78**, 1–21.

Telfer, M. W., and Thomas, D. S. G., 2006. Complex Holocene lunette dune development, South Africa: implications for paleoclimate and models of pan development in arid regions. *Geology*, **34**(10), 853–856.

Telfer, M. W., Bailey, R. M., Burrough, S. L., Stone, A. E. S., Thomas, D. S. G., and Wiggs, G. S. F., 2010. Understanding linear dune chronologies: insights from a simple accumulation model. *Geomorphology*, **120**(3–4), 195–208.

Teller, J. T., Glennie, K. W., Lancaster, N., and Singhvi, A. K., 2000. Calcareous dunes of the United Arab Emirates and Noah's flood: the postglacial reflooding of the Persian (Arabian) Gulf. *Quaternary International*, **68–71**, 297–308.

Thomas, D. S. G., 2013. Reconstructing paleoenvironments and palaeoclimates in drylands: what can landform analysis contribute? *Earth Surface Processes and Landforms*, **38**(1), 3–16. 2011 = doi:10.1002/esp.3190.

Tripaldi, A., and Forman, S. L., 2007. Geomorphology and chronology of Late Quaternary dune fields of western Argentina. *Palaeogeography Palaeoclimatology Palaeoecology*, **251**(2), 300–320.

Tsoar, H., Blumberg, D. G., and Stoler, Y., 2004. Elongation and migration of sand dunes. *Geomorphology*, **57**(3–4), 293–302.

Warren, A., 2013. *Dunes: Dynamics, Morphology, History.* Chichester: Wiley-Blackwell.

Wasson, R. J., Fitchett, K., Mackey, B., and Hyde, R., 1988. Large-scale patterns of dune type, spacing and orientation in the Australian continental dunefield. *Australian Geographer*, **19**(1), 89–104.

Winterbottom, S. J., and Dawson, T., 2005. Airborne multi-spectral prospection for buried archaeology in mobile sand dominated systems. *Archaeological Prospection*, **12**(4), 205–219.

Wright, D. K., Forman, S. L., Waters, M. R., and Ravesloot, J. C., 2011. Holocene eolian activation as a proxy for broad-scale landscape change on the Gila River Indian Community, Arizona. *Quaternary Research*, **76**(1), 10–21.

Cross-references

Archaeological Stratigraphy
Eolian Settings: Loess
Geomorphology
Lake Mungo and Willandra
Optically Stimulated Luminescence (OSL) Dating
Paleoenvironmental Reconstruction

ETHNOGEOARCHAEOLOGY

Georgia Tsartsidou
Ephoreia of Palaeoanthropology-Speleology, Athens, Greece

Synonyms

Geoethnoarchaeology

Definition

Ethnogeoarchaeology: Geological methods and observations that address archaeological questions and are applied in an ethnographic context/environment.

Ethnographic environment: Extant traditional societies that preserve traditional ways of living and subsistence strategies.

Essential concepts of ethnogeoarchaeology and historical perspective

Geoarchaeology refers to any earth-science concept, technique, or knowledge base applicable to the study of artifacts and processes involved in the creation of the archaeological record (Rapp and Hill 1998, 1–2). Ethnoarchaeology is the study of extant societies with the goal of answering archaeological questions about site and artifact formation that can be applied to the interpretation of archaeological sites. The combination of the two fields – geoarchaeology and ethnoarchaeology – leads to ethnogeoarchaeology, which can be defined as the conduct of geoarchaeological research in societies that preserve traditional ways of living in order to use such observations and analytical results to gain insights into the structure of ancient societies and their subsistence strategies.

The first geoarchaeological studies conducted in ethnographic environments intended to make geological observations of ongoing phenomena that were related to archaeological problems being encountered at nearby sites. Such a study was pioneered by McIntosh (1974) and was focused on mud wall decay in Hani, a modern village of western Ghana, in order to learn about the deterioration process as it occurs in modern time so that the ideas could be applied to the study of an archaeological site in the vicinity at Begho. The ethnographic research was aimed at describing and understanding the processes of decay and the subsequent rearrangement of altered material during all phases of deterioration in order to recognize former walls in an archaeological context. The modern structures under study were built of unfired courses of puddle mud (terre pisé) or of wattle and daub, both roofed with thatch. It was seen that both the puddle mud and wattle-and-daub walls decayed readily and that the process continued until the wall remains were protected by overlying deposits of previously intact wall material. Within the archaeological site, environmental factors (such as humidity and acidity of the local soil as well as animal and root activity) plus the use of local soils for construction had made the identification of decayed walls almost impossible. The results of ethnogeoarchaeological observation helped in recognizing the remains of former buildings within the archaeological site. The excavators also determined that, in almost all cases, it was impossible to distinguish archaeologically between terre pisé and wattle and daub.

Another pioneering study based on geoarchaeological observations was conducted by Gifford and Behrensmeyer (1977) on the northeastern shore of Lake Turkana, Kenya. They were investigating site formation processes, specifically the interplay of geological factors and human activities at a recent hunting/gathering campsite established by a small group of Daasanach people. The goal was to investigate, among several matters, the sedimentation rate and resultant sedimentary structures, the bone taphonomy and preservation, and the identification of subsistence activities in a controlled, well-described, temporal geomorphic context (see also below).

Subsequent ethnogeoarchaeological studies employed geologic methods and scientific techniques that sought to detect anthropogenic traces left in the sediments. These studies included micromorphology, analysis of mineral components (phytoliths and spherulites), soil mineralogical analyses, and organic residues of the sediments (phosphorus concentrations, heavy mineral identifications, etc.). Research conducted to date has been directed largely toward understanding the microscopic record, and new developments are still taking place.

Most recently, the study of site formation processes has emerged as the newest field of ethnogeoarchaeological research. It involves studies on both macroscopic and microscopic scales (Schiffer, 1987) that investigate the accumulation, abandonment, and degradation of sites (Shahack-Gross, 2007). Accumulation and abandonment have been studied through ethnographic and archaeological research (Shahack-Gross, 2007). Accumulation processes include those of site buildup, such as construction of architectural features (e.g., houses, hearths) and disposal activities (e.g., knapping waste, dumping patterns) (see Hayden and Cannon, 1983). Abandonment processes affect patterning in the archaeological record and involve regional as well as site-specific studies in ethnographic and archaeological contexts (Cameron and Tomka, 1993). Degradation processes occur throughout the life history of settlements as well as after their abandonment. These are usually referred to as taphonomic and diagenetic processes, and they are studied mostly using natural science approaches emphasizing biological, chemical, and physical methods and techniques (Schiffer, 1987).

Applications: in greater detail

Micro-artifacts

A definition of size that differentiates micro-artifacts from macro-artifacts has been proposed by S. Weiner, a pioneer in the application of scientific methods to deciphering the archaeological record. In his definition, “one millimeter or so is the cutoff between fragments that can be discerned by the naked eye and those that cannot” (Weiner, 2010, 229). The small artifacts (e.g., bone fragments, lithics, charcoal pieces) enter into the substrate by trampling, and they therefore have a better chance of being preserved than larger artifacts (Gifford, 1978). They also have a better chance of being recovered close to the location where they were produced (O’Connell, 1987), that is, as part of a primary deposit.

A pioneer study of micro-artifact assemblages was conducted by Gifford (1978), who examined a Daasanach hunter/gatherer site on the shore of Lake Turkana that was occupied by a small group for four days. She observed a size-dependent sorting of micro-artifacts, and she recorded nine times the number of bone fragments recovered from the subsurface than had been visible on the ground.

A later study conducted in Israel by Rosen (1986) investigated micro-artifact assemblages from the floors of tells; this information was combined with site formation research in order to identify activity areas. Rosen included aspects of accretion and erosion in tell sites to show the landscape formation processes that affect mounds and how humans influence this environment. This and later research conducted by Rosen was inspired by several ethnoarchaeological studies dealing with micro-artifact accumulation on earth floors conducted mostly in Central American contexts (Hayden and Cannon, 1983). The basic finding of those New World studies was that small fragments trampled into floors during the course of specific activities (e.g., flint, pottery, bones, and charcoal) represent clearer evidence for those activities than that available from the macroscopic artifactual record (Hayden and Cannon, 1983). Rosen developed a procedure to obtain data on micro-artifacts within tell sites (Rosen, 1989, 1993), and she applied it at sites such as Tell Miqne, Tell Batash, Tell Halif, Lachish, and Shiqmim.

Biological material

Phytoliths are microscopic mineral forms produced by certain plants within their tissues. The best-preserved ones

Ethnogeoarchaeology, Figure 1 Photograph showing a section dug into the clay floor of an abandoned house at Sarakini, Greece. Thick oak beams forming the base are covered by a mud mixture and then overlain by successive clay laminae that represent floor replasterings. The loose sediment on the floor reflects debris accumulated after abandonment as well as secondary use remains (rye straw).

Ethnogeoarchaeology, Figure 2 Photograph showing a section dug into the floor of an abandoned barn at Sarakini, Greece. Bedrock is overlain by thin, compacted layers of decayed straw and soil. Fallen thatch covers the barn floor.

are composed of hydrated silica (opal), and they remain in the soil of archaeological sites as phytolith concentrations resulting from dissolution or degradation of plant organic matter. They are usually trampled into floors, thereby providing evidence of human activities involving the plants identifiable by their phytoliths.

A recent ethnogeoarchaeological study of abandoned structures conducted at a Greek village in Thrace, northern Greece (Tsartsidou et al., 2008), looked into phytoliths as indicators of activity areas within an agropastoral community. The structures analyzed had been abandoned for more than 30 years, and therefore, the transformation of the organic remains had already led to complete decay, leaving the place much like an archaeological site. The buildings and village layout were still preserved, and a local informant verified their functional uses. Sediment samples were collected from diverse locations and analyzed (Figures 1 and 2). The results demonstrated the value of phytoliths as a useful tool for identifying some activity areas (e.g., barns, Figure 2) while indicating the difficulties of recognizing others. For example, the living floors of houses, made of clay (Figure 1), were devoid of phytoliths, whereas the clay floors of storage areas had more phytoliths. The rich phytolith concentrations of the ground floor stables (originating from residual dung) contrasted markedly with the paucity of phytoliths associated with the living areas of the second story floor above. Stabling areas of seasonal sites were sometimes cleaned and the dung used as fertilizer; in such cases, there was no evidence of stabling activities based on phytoliths, thereby demonstrating the difficulty of recognizing such an activity area in an archaeological context – but offering a clue to the possible presence of an agropastoral community that exploited the dung for the fields. The threshing floors were also not easily identified since most of them were devoid of phytoliths, and the phytoliths that were found originated from the hard layer of dung often used to coat the floor.

The results of these ethnogeoarchaeological observations were applied to a pottery Neolithic site at Makri in the broader geographical area (Tsartsidou et al., 2009). Aspects of construction practices and use of space were identified through the analysis of phytolith assemblages from the floors of the site. A possible change in the use of space was also identified in a sequence of superposed floors, where one of them lacked the consistent presence of dung phytoliths and incorporated an assemblage related more to straw used in construction. Finally, the rich husk phytolith remains from wheat and barley seeds that accumulated significantly in a certain area of the site pointed to a central storage facility, probably of communal character.

Phytolith analyses have proven very useful for the identification of dung remains (Shahack-Gross et al., 2003; Tsartsidou et al., 2008). Dung may have been used in the past for several purposes, including as building material, fuel, fertilizer, etc. It can therefore be found in various contexts within archaeological sites, such as enclosures, middens, trash pits, floors, walls, and other deposits. Various geoarchaeological studies have been conducted in ethnographic environments all over the world in order to learn about the ways dung has been used as well as the diagenetic processes it undergoes after deposition (Brochier et al., 1992; Canti, 1997). Laboratory studies of fresh ovicaprine droppings and comparative explorations of four Neolithic sites from France and Greece conducted by Brochier (1983) showed that prehistoric herding could be identified by the occurrence of spherulites, i.e., microscopic crystals of calcium salt formed in the animals' guts (Canti, 1999) that are frequently found in association with grass phytoliths. The encouraging results of this initial study led Brochier et al. (1992) to study modern stock pen deposits, combining sedimentology, archaeology, and ethnography in order to identify traces of past herding and isolate variables that affect the preservation of dung in archaeological sites. The study was conducted in open-air sites, caves, and rock shelters of Sicily, where traditional herding was still performed. The results verified that spherulites, phytoliths, layers of burnt manure, and rock polish in caves are diagnostic indicators of herding, and these indicators are preserved in open-air sites and beneath roofed structures under conditions of rapid burial. Diagenetic gypsum has been also identified as an indicator of the former presence of quantities of vegetal matter.

Apart from phytoliths and spherulites, researchers have reported other characteristic features that constitute evidence of decayed dung: unique, undulating, microlaminated structures in sediments associated with substantial amounts of phytoliths identified by thin section analysis (Shahack-Gross et al., 2003) and the presence of phosphate concentrations (Macphail et al., 2004) and organic residues. High $\delta\ ^{15}N$ values point to preserved organic matter in degraded livestock dung, and $\delta\ ^{13}N$ values proved to be helpful for distinguishing grazing from browsing animals (Codron et al., 2005).

Shahack-Gross et al. (2003, 2004) carried out studies in Kenya among Maasai pastoralists, where the basic approach was to follow the accumulation and degradation processes related to the formation of livestock enclosures by sampling sediments along a taphonomic sequence of abandoned Maasai settlements. Sediments were sampled not only from enclosures but also from houses, hearths, gate areas, and trash pits; formation processes were monitored for over 40 years after abandonment using geoarchaeological techniques that included infrared spectroscopy for bulk mineral identifications, micromorphology for sediment microstructure attributes, and quantitative phytolith analyses for differentiating enclosures from other sediments within and around the settlements. The methods developed by Shahack-Gross et al. (2003, 2004) have been applied to archaeological sites in Israel and are most useful for inferring subsistence practices and activity areas (Shahack-Gross et al., 2005). Furthermore, pastoral practices and the use of dung as fuel in Bronze Age and Iron Age sites of Israel have been tested (Katz et al., 2007; Albert et al., 2008; Shahack-Gross and Finkelstein, 2008).

Finally, an ethnogeoarchaeological study of accumulation processes in Bedouin camps in southern Israel conducted by Shahack-Gross and Finkelstein (2008) has shown that livestock dung in the desert ecosystem differs from that in the Mediterranean ecosystem by having much lower phytolith concentrations. In addition, they showed that seasonality of herding camps in the desert might be discerned by phytolith analysis. They also discovered that spherulites are better preserved in arid contexts than in the moister Mediterranean zone. Shahack-Gross and Finkelstein (2008) applied these results to the study of sediments from Atar Haroa, an Iron Age site in the Negev Highlands near Sde Boqer, and proposed that the economic base of this site was centered on pure pastoralism rather than agropastoralism.

Micromorphology

Micromorphology is the study of undisturbed soils and soft sediments using petrographic thin sections (Goldberg and Whitbread, 1993). It has been applied to numerous archaeological problems since it can identify anthropogenic impacts by recognizing effects of very small scale within sediments (Courty et al., 1989) and therefore help to diagnose otherwise invisible human and natural activities.

Goldberg and Whitbread (1993) pioneered a study that investigated the formation of floors in an abandoned Bedouin camp near Be'er Sheva in Israel; the goal was to define the living floor using micromorphological analysis (both qualitative observations and quantitative image analysis). They showed that the living floor could be identified based on its relatively higher compactness and subhorizontal, parallel-elongated voids. They highlighted the problem of identifying earthen floors in archaeological sites and stressed that microscopic features are more reliable than macroscopic ones when dealing with "dirt," rather than plastered or paved floors (see also Gé et al., 1993). Goldberg and Whitbread (1993) also reported that living floor features are more easily identifiable in clayey sediments because they are more easily compacted than sandy sediments and develop the characteristic subhorizontal voids more readily. Later studies have indeed identified these micromorphological features in archaeological sites (Shahack-Gross et al., 2003, 2005; Berna et al., 2007; Shahack-Gross and Finkelstein, 2008).

In order to achieve greater interpretative detail from the repeated fine plastering events observed in the structures at the Neolithic site of Çatalhöyük in central Turkey, Boivin (2000) investigated a modern rural community in Rajasthan, northwestern India. The occupants of the village repeatedly replastered rooms in their houses following various rules of hygiene as well as major social events on the calendar, religious or civil (births, deaths, marriages, etc.). Replastering was not related to some constructional method or necessity. Temporal cycles were identified in the floor sequence of Rajasthani houses, with repeated replasterings involving variations in materials used depending upon the occasion. These ethnoarchaeological observations were compared to the repeated replasterings of floors and walls at the Neolithic site of Çatalhöyük. Archaeological study of these floors and wall sequences suggests in their cyclical pattern involving techniques and materials a possibly similar temporal rhythm of associated rituals.

Another ethnogeoarchaeological study was conducted at nineteenth- and early twentieth-century turf houses on a farm in Iceland (Milek, 2006). The research included observations regarding the physical properties of turf as a building material, the techniques used in construction and maintenance, as well as the collapse and decay of the buildings. The floors of a residential building and a sheep stable were analyzed, the activities performed were investigated, and samples for micromorphological analysis were collected from trenches excavated into the floors. The results determined again that the study of micro-artifacts shows greater potential in recognizing activity areas than macro-artifact analysis, and combining this with micromorphology provides strong evidence of floor formation processes and the human actions conducted on them. The results were then applied to archaeological sites of the Viking Age in Iceland in order to explore the use of space and understand the depositional history of the archaeological floors.

Micromorphological analysis of five different types of fires (sleeping fires, communal cooking fires, etc.) was conducted among the Hadza, hunting and gathering people of Tanzania, in order to identify the anthropogenic nature of the fires, the burning intensity, and the type of fuel used (Mallol et al., 2007). The results show that micromorphology can be helpful in distinguishing between natural and anthropogenic fires as well as detecting the burning intensity; it can thus serve as a tool for distinguishing among different types of fires, e.g., telling cooking fires apart from sleeping fires. Implications of such research include greater understanding of how and when such combustion features are preserved archaeologically and signs that bear upon interpretation of their function.

Goodman-Elgar (2008) studied the formation of archaeological deposits through ethnogeoarchaeological research into highly weathered contemporary adobe structures of an abandoned domestic compound on the Taraco Peninsula, Bolivia. The intent was to use thin section micromorphology to ascertain the composition of construction materials and their sources, identify features associated with the use of the structures, and characterize the processes by which they deteriorated over time. The ethnographic site was composed of rooms for different functions that had been uninhabited for over 50 years. Geoarchaeological samples were collected from intact and weathered adobes, earthen hearths, mud plaster, and floors. Conclusions from analysis showed that (1) organic material (e.g., reed thatch of roof fall) attracted soil fauna leading to bioturbation of floor layers (beaten earth), (2) the most stable indicators of anthropogenic activities were the reddened adobes and earth patches ("rubified peds") associated with hearths, and (3) based on general observations, a devolutionary sequence could be constructed for the progressive degradation of adobe architecture and redeposition of its erosional materials. The results were compared with data from prehistoric sites excavated on the Taraco Peninsula (Chiripa, Kala Uyuni, and Sonaji). The comparison showed both parallel and significant differences in the construction materials and techniques used.

Research carried out in shell middens of Tierra del Fuego followed an ethnoarchaeological approach to test new developments in archaeology (Godino et al., 2011). The archaeological sites of this area (Beagle Channel) are shell middens formed by multiple episodes of shell deposition mixed with the remains from diverse production and consumption activities. The ethnographic research was conducted among the Yamanas, a hunter-fisher-gatherer society with a high level of marine resources management. The lines of evidence examined were micromorphology, phytolith analysis, and functional lithic analysis in order to identify different occupation episodes and unravel the spatial organization of the daily activities aiming at understanding social dynamics in hunter-fisher-gatherer societies. The results have been applied to two archaeological sites of the Beagle Channel: Tùnel VII and Lanashuaia I. Micromorphological analysis proved helpful in interpretations relative to site function and intensity of frequentation. The application of micromorphology together with phytolith analysis allowed greater stratigraphic definition as well as evaluation of the effects of taphonomic processes on the transformation of buried materials into the final archaeological record. Finally, it successfully recognized specific spatial patterns inside the dwellings and defined the actual function of anthropic features such as fireplaces.

Soil chemical analysis

Soil chemical analysis is based on the premise that activities performed in the same place over a long period of time leave behind distinct chemical signatures in the form of residues that are trapped in the soil where they remain relatively unaffected over time (Barba and Ortiz, 1992; Parnell et al., 2002a, b). Although soil chemical analysis in archaeology encompasses a wide range of procedures, some of the most promising signatures come from analyses of phosphorus and heavy metals, e.g., copper, iron, mercury, manganese, lead, and zinc (Wells et al., 2000; Parnell et al., 2002a).

Ethnographic studies have been conducted in order to demonstrate the interpretive value of chemical analysis (Hayden and Cannon, 1983; Smyth, 1990; Barba and Ortiz, 1992; Manzanilla, 1996; Middleton and Price 1996; Fernández et al., 2002; Parnell et al., 2002a, b). Some exemplary research has been done in Guatemala. Phosphate analysis of sediments was conducted at the contemporary Qéqchi Maya village in order to investigate household activities and establish their soil chemical signatures (Terry et al., 2004). The results were then applied at the archaeological site of Aguateca. The study showed high concentrations of phosphorus in the kitchen, the refuse dump, and the runoff area from the refuse dump.

Similarly, ethnogeoarchaeological work by Barba and Ortiz (1992) demonstrated that phosphorus levels correlate with known activities; high concentrations were found in the kitchen floors and eating areas, whereas soils of the discard area for water used in maize soaking showed moderate levels and walkway soils exhibited low concentrations.

Finally, a study of two fish processing sites used by Cupiit Eskimos in southwestern Alaska revealed high phosphorus and other element concentrations in specific locations, such as fish drying racks (Knudson et al., 2004).

Summary

Ethnogeoarchaeology is the application of geologically based techniques to the study of sediments as well as the cultural traces within them in extant societies in order to gain ideas about the structure of ancient societies and their activities. These techniques have included granulometry, phosphorus concentrations, heavy mineral identifications, mineral component analysis, study of micro-artifacts, and micromorphology. To this end, ethnographic sites have been explored all over the world, and the results have been applied in archaeological sites of the same geographic area.

Although the results from applications of geoscience methods have been encouraging, further work on new samples obtained under controlled ethnogeoarchaeological conditions is nevertheless needed to corroborate and enhance these initial insights into human dynamics. One problem is that, with few exceptions, most studies are of local importance and focused on specific materials and processes. In so doing, they provide only a limited part of what should be a coherent set of characteristics leading to a better understanding of archaeological site formation. It is therefore necessary to design more holistic and multidisciplinary approaches to conducting ethnographic explorations using the prism of geoarchaeology.

Bibliography

Albert, R. M., Shahack-Gross, R., Cabanes, D., Gilboa, A., Lev-Yadun, S., Portillo, M., Sharon, I., Boaretto, E., and Weiner, S., 2008. Phytolith-rich layers from the Late Bronze and Iron Ages at Tel Dor (Israel): mode of formation and archaeological significance. *Journal of Archaeological Science*, **35**(1), 57–75.

Barba, L., and Ortiz, A., 1992. Análisis químico de pisos ocupación: Un caso etnográfico en Tlaxcala, Mexico. *Latin American Antiquity*, **3**(1), 63–82.

Berna, F., Behar, A., Shahack-Gross, R., Berg, J., Boaretto, E., Gilboa, A., Sharon, I., Shalev, S., Shilshtein, S., Yahalom-Mack, N., Zorn, J. R., and Weiner, S., 2007. Sediments exposed to high temperatures: reconstructing pyrotechnological processes in Late Bronze Age and Iron Age strata at Tel Dor (Israel). *Journal of Archaeological Science*, **34**(3), 358–373.

Boivin, N., 2000. Life rhythms and floors sequences: excavating time in rural Rajasthan and Neolithic atalhöyük. *World Archaeology*, **31**(3), 367–388.

Brochier, J. E., 1983. Combustion et parcage des herbivores domestiques. Le point de vue du sédimentologue. *Bulletin de la Societé Préhistorique Française*, **80**(5), 143–145.

Brochier, J. E., Villa, P., Giacomarra, M., and Tagliacozzo, A., 1992. Shepherds and sediments: geo-ethnoarchaeology of pastoral sites. *Journal of Anthropological Archaeology*, **11**(1), 47–102.

Cameron, C. M., and Tomka, S. A. (eds.), 1993. *Abandonment of Settlements and Regions: Ethnoarchaeological and Archaeological Approaches*. Cambridge: Cambridge University Press.

Canti, M. G., 1997. An investigation of microscopic calcareous spherulites from herbivore dungs. *Journal of Archaeological Science*, **24**(3), 219–231.

Canti, M. G., 1999. The production and preservation of faecal spherulites: animals, environment and taphonomy. *Journal of Archaeological Science*, **26**(3), 251–258.

Codron, D., Codron, J., Lee-Thorp, J. A., Sponheimer, M., and De Ruiter, D., 2005. Animal diets in the Waterberg based on stable isotopic composition of faeces. *South African Journal of Wildlife Research*, **35**(1), 43–52.

Courty, M.-A., Goldberg, P., and Macphail, R. I., 1989. *Soils and Micromorphology in Archaeology*. Cambridge: Cambridge University Press.

Fernández, F. G., Terry, R. E., Inomata, T., and Eberl, M., 2002. An ethnoarchaeological study of chemical residues in the floors and soils of Q'eqchi' Maya houses at Las Pozas, Guatemala. *Geoarchaeology*, **17**(6), 487–519.

Gé, T., Courty, M.-A., Matthews, W., and Wattez, J., 1993. Sedimentary formation processes of occupation surfaces. In Goldberg, P., Nash, D. T., and Petraglia, M. D. (eds.), *Formation Processes in Archaeological Context*. Madison, WI: Prehistory Press, pp. 149–163.

Gifford, D. P., 1978. Ethnoarchaeological observations of natural processes affecting cultural materials. In Gould, R. A. (ed.), *Explorations in Ethnoarchaeology*. Albuquerque: University of New Mexico Press, pp. 77–101.

Gifford, D. P., and Behrensmeyer, A. K., 1977. Observed formation and burial of a recent human occupation site in Kenya. *Quaternary Research*, **8**(3), 245–266.

Godino, I. B., Álvarez, M., Balbo, A., Zurro, D., Madella, M., Villagrán, X., and French, C., 2011. Towards high-resolution shell midden archaeology: experimental and ethnoarchaeology in Tierra del Fuego (Argentina). *Quaternary International*, **239** (1–2), 125–134.

Goldberg, P., and Whitbread, I., 1993. Micromorphological study of a Bedouin tent floor. In Goldberg, P., Nash, D. T., and Petraglia, M. D. (eds.), *Formation Processes in Archaeological Context*. Madison, WI: Prehistory Press, pp. 165–188.

Goodman-Elgar, M., 2008. The devolution of mudbrick: ethnoarchaeology of abandoned earthen dwellings in the Bolivian Andes. *Journal of Archaeological Science*, **35**(12), 3057–3071.

Hayden, B., and Cannon, A., 1983. Where the garbage goes: refuse disposal in the Maya Highlands. *Journal of Anthropological Archaeology*, **2**(2), 117–163.

Katz, O., Gilead, I., Bar (Kutiel), P., and Shahack-Gross, R., 2007. Chalcolithic agricultural life at Grar, Northern Negev, Israel: dry farmed cereals and dung-fueled hearths. *Paléorient*, **33**(2), 101–116.

Knudson, K. J., Frink, L., Hoffman, B. W., and Price, T. D., 2004. Chemical characterization of Arctic soils: activity area analysis in contemporary Yup'ik fish camps using ICP-AES. *Journal of Archaeological Science*, **31**(4), 443–456.

Macphail, R. I., Cruise, G. M., Allen, M. J., Linderholm, J., and Reynolds, P., 2004. Archaeological soil and pollen analysis of experimental floor deposits; with special reference to Butser Ancient Farm, Hampshire, UK. *Journal of Archaeological Science*, **31**(2), 175–191.

Mallol, C., Marlowe, F. W., Wood, B. M., and Porter, C. C., 2007. Earth, wind, and fire: ethnoarchaeological signals of Hadza fires. *Journal of Archaeological Science*, **34**(12), 2035–2052.

Manzanilla, L., 1996. Corporate groups and domestic activities at Teotihuacan. *Latin American Antiquity*, **7**(3), 228–246.
McIntosh, R. J., 1974. Archaeology and mud wall decay in a West African village. *World Archaeology*, **6**(2), 154–171.
Middleton, W. D., and Price, T. D., 1996. Identification of activity areas by multi-element characterization of sediments from modern and archaeological house floors using Inductively Coupled Plasma-Atomic Emission Spectroscopy. *Journal of Archaeological Science*, **23**(5), 673–687.
Milek, K. B., 2006. *Houses and Households in Early Icelandic Society: Geoarchaeology and the Interpretation of Social Space*. PhD thesis, University of Cambridge.
O'Connell, J. F., 1987. Alyawara site structure and its archaeological implications. *American Antiquity*, **52**(1), 74–108.
Parnell, J. J., Terry, R. E., and Sheets, P., 2002a. Soil chemical analysis of ancient activities in Cerén, El Salvador: a case study of a rapidly abandoned site. *Latin American Antiquity*, **13**(3), 331–342.
Parnell, J. J., Terry, R. E., and Nelson, Z., 2002b. Soil chemical analysis applied as an interpretive tool for ancient human activities at Piedras Negras, Guatemala. *Journal of Archaeological Science*, **29**(4), 379–404.
Rapp, G. R., and Hill, C. L., 1998. *Geoarchaeology: The Earth-Science Approach to Archaeological Interpretation*. New Haven: Yale University Press.
Rosen, A. M., 1986. *Cities of Clay: The Geoarchaeology of Tells*. Chicago: University of Chicago Press.
Rosen, A. M., 1989. Ancient town and city sites: A view from the microscope. *American Antiquity*, **54**(3), 564–578.
Rosen, A. M., 1993. Microartifacts as a reflection of cultural factors in site formation. In Goldberg, P., Nash, D. T., and Petraglia, M. D. (eds.), *Formation Processes in Archaeological Context*. Madison, WI: Prehistory Press, pp. 141–148.
Schiffer, M. B., 1987. *Formation Processes of the Archaeological Record*. Salt Lake City: University of Utah Press.
Shahack-Gross, R., 2007. Approaches to understanding formation of archaeological sites in Israel: Materials and processes. *Israel Journal of Earth Sciences*, **56**, 73–86.
Shahack-Gross, R., and Finkelstein, I., 2008. Subsistence practices in an arid environment: a geoarchaeological investigation in an Iron Age site the Negev Highlands, Israel. *Journal of Archaeological Science*, **35**(4), 965–982.
Shahack-Gross, R., Marshall, F., and Weiner, S., 2003. Geo-ethnoarchaeology of pastoral sites: the identification of livestock enclosures in abandoned Maasai settlements. *Journal of Archaeological Science*, **30**(4), 439–459.
Shahack-Gross, R., Marshall, F., Ryan, K., and Weiner, S., 2004. Reconstruction of spatial organization in abandoned Maasai settlements: implications for site structure in the Pastoral Neolithic of East Africa. *Journal of Archaeological Science*, **31**(10), 1395–1411.
Shahack-Gross, R., Albert, R.-M., Gilboa, A., Nagar-Hilman, O., Sharon, I., and Weiner, S., 2005. Geoarchaeology in an urban context: the uses of space in a Phoenician monumental building at Tel Dor (Israel). *Journal of Archaeological Science*, **32**(9), 1417–1431.
Smyth, M. P., 1990. Maize storage among the Puuc Maya: the development of an archaeological method. *Ancient Mesoamerica*, **1**(1), 51–69.
Terry, R. E., Fernández, F. G., Parnell, J. J., and Inomata, T., 2004. The story in the floors: chemical signatures of ancient and modern Maya activities at Aguateca, Guatemala. *Journal of Archaeological Science*, **31**(9), 1237–1250.
Tsartsidou, G., Lev-Yadun, S., Efstratiou, N., and Weiner, S., 2008. Ethnoarchaeological study of phytolith assemblages from an agro-pastoral village in northern Greece (Sarakini): development and application of a Phytolith Difference Index. *Journal of Archaeological Science*, **35**(3), 600–613.
Tsartsidou, G., Lev-Yadun, S., Efstratiou, N., and Weiner, S., 2009. Use of space in a Neolithic village in Greece (Makri): phytolith analysis and comparison of phytolith assemblages from an ethnographic setting in the same area. *Journal of Archaeological Science*, **36**(10), 2342–2352.
Weiner, S., 2010. *Microarchaeology: Beyond the Visible Archaeological Record*. Cambridge: Cambridge University Press.
Wells, E. C., Terry, R. E., Parnell, J. J., Hardin, P. J., Jackson, M. W., and Houston, S. D., 2000. Chemical analyses of ancient anthrosols in residential areas at Piedras Negras, Guatemala. *Journal of Archaeological Science*, **27**(5), 449–462.

Cross-references

Analysis of Carbon, Nitrogen, pH, Phosphorus, and Carbonates as Tools in Geoarchaeological Research
Experimental Geoarchaeology
Field Geochemistry
Living Surfaces
Pastoral Sites
Site Formation Processes
Soil Micromorphology
Tells
Trampling

EXPERIMENTAL GEOARCHAEOLOGY

Richard I. Macphail
Institute of Archaeology, University College London, London, UK

Synonyms

Experimental archaeology/archaeometry

Definition

Experiments in archaeology that further our understanding of geoarchaeology in its broadest sense.

Introduction

Experimental geoarchaeology has been practiced systematically at least since the 1960s in the UK (Bell, 2009), with particularly active times for reconstructions and experiments occurring during the 1970s and 1980s in Europe and North America. The last decade has also seen a renewal of interest universally. Originally, earth science experiments attempted to replicate natural processes (e.g., with the use of flume tanks) and then expanded into studying human activities (constructions, farming, and artifact manufacturing) and postdepositional effects on soils and sediments and the artifacts within them (cf. taphonomy). In addition, archaeological "farms" and open-air museums have also been seen as opportunities to infer past uses of space and activities and to learn how these can be identified from the geoarchaeological record – e.g., "Viking" L'Anse aux Meadows, Newfoundland, Canada, "seventeenth century" Plymouth Plantation, Massachusetts, USA, and (see below) Butser Ancient Farm, Lejre Museum, and West Stow Anglo-Saxon Village. Lastly, individual or small study groups have conducted numerous small experiments and produced their own reference data; this kind of research is often unpublished, however. Compared to some short-lived (~3 year) research projects, and serendipitous analyses of material from open-air museums, only a few well-constructed research studies have been substantially longitudinal; the best examples are the Experimental Earthworks which have a planned monitored life of 128 years.

Care has been taken in this entry not to include within experimental geoarchaeology ethnographic observations sensu stricto or information stemming from archaeological site studies in general, although these are both crucial parallel sources of information. In addition, such data contribute to the construction of experiments and the testing of experimental results – the last a very necessary step. Finally, it should be noted that some overlap with experimental archaeometry, geomorphology, soil science, and agronomy is inevitable, along with an often essential holistic paleoenvironmental pluri-disciplinary approach.

This entry selectively examines experimental geoarchaeology from the perspective of:

Natural processes: examples of slope processes and colluvium and marine inundation
Constructions: examples of turf structures and earthworks, lime plaster, and disuse and destruction features
Activities: examples of fires, ovens and furnaces, animal management, and cultivation
Occupation floors and use of internal space: comparison of domestic and stabling space

Natural processes

Some of the classic studies of slope deposits (which aid the understanding of Quaternary sediments, for example) were carried out on the redeposition of aeolian loess in Europe using flumes and soil micromorphology (Mücher and Morozova, 1983). These studies were able to differentiate between loess redeposited simply by (1) rainsplash (e.g., unsorted and unlaminated), (2) rainwash (overland flow with raindrop impact and laminated sediments with some mineral and size sorting), and (3) flow without splash ("after-rain flow" or meltwater flow) leading to some very well-laminated and sorted deposits, which were also mineralogically differentiated. In addition, when freezing and thawing factors are added, bare soil erosion increases in direct proportion to soil moisture (Ferrick and Gatto, 2004). These findings are directly relevant to understanding the supposed cold and humid sedimentary conditions associated with hominin occupation (artifact concentrations) in the upper deposits at Lower Paleolithic Boxgrove, UK. Experiments related to agronomy and soil erosion have also found that rainsplash disrupts soil aggregates and aids soil slope movement and that soil aggregate types from different land uses vary from the most stable to the least stable as follows: pasture→woodland→arable. Resulting hillwash colluvia develop as waterlain sediments, and this is suggested not only by modeling (Farres et al., 1992), but it is also found in reality. Such findings have been applied to both environmental and land-use history reconstructions, for instance, plough/bare ground-induced soil erosion.

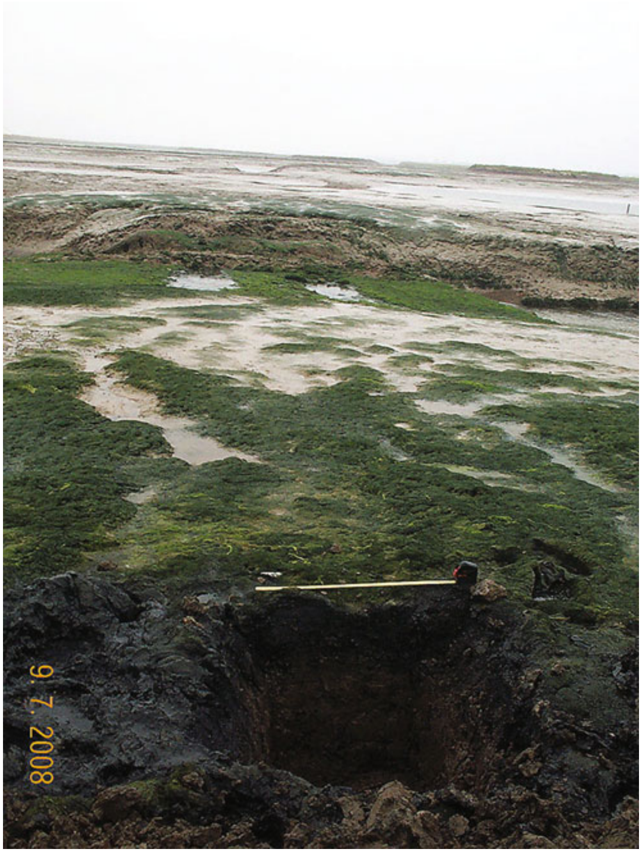
More recently, the modern effects of sea-level rise on coastal archaeology have begun to be of concern. Effects of past marine inundation on low-lying early Holocene sites as sea levels rose (i.e., as ice sheets retreated) have already been observed from excavated intertidal sites, but the monitored effects of flooding are only now being recorded. As a way of mitigating the future effects of marine flooding, "planned retreat" has led to the experimental establishment of salt marsh when the sea wall around reclaimed land was breached on purpose at Wallasea Island, Essex, UK (Macphail et al., 2010). The area was originally medieval reclaimed land. Control profiles from the current sea wall-protected arable fields and grassland were compared to a 2-year-old marine-flooded grassland soil (Figures 1, 2, and 3). The chief results were:

- The rise in base level causes the onset of hydromorphic conditions.
- A strongly marked rise in saturation extract conductivity ("salinity") by 20–60 times due to marine inundation (hence soil dispersion by Na^+ in ancient flooded soils).
- Terrestrial surfaces become sealed by microlaminated salt marsh sediments, with marine alluvium also washing down profile.
- At low tide, sediments undergo rapid ripening (subaerial weathering) over a 2-year experimental timescale, with detrital organic matter (e.g., seaweed) becoming oxidized and ferruginized.
- Biostratigraphy becomes salt marsh and tidal flat in character (e.g., foraminifera); pollen spectra change from local (arable) to regional/extra-regional with the North Sea being the potential catchment area (anomalously high tree pollen concentrations).

Constructions

Turf structures and earthworks

The first 1960s experimental earthworks in the UK were linear bank and ditch constructions designed to study buried artifact taphonomy, but which also supplied information on the changing morphology of the bank and ditch fill, as monitored over 1, 2, 4, 8, 16, and 32 years, with future recording scheduled for 64 and 128 years (Bell et al., 1996). The 1960 Overton Down earthwork (Wiltshire, UK) on chalk was most recently studied in 1992 (after 32 years). Turf bank- and chalk bank-buried rendzina soils (rendols) were compared to nearby control profiles. Field observations showed a decrease in thickness in the Ah horizon, from ~180 mm to 90–100 mm, in part because of organic matter loss (from ~11.0 % to 7.59–7.88 % organic C); acidity also increased under the

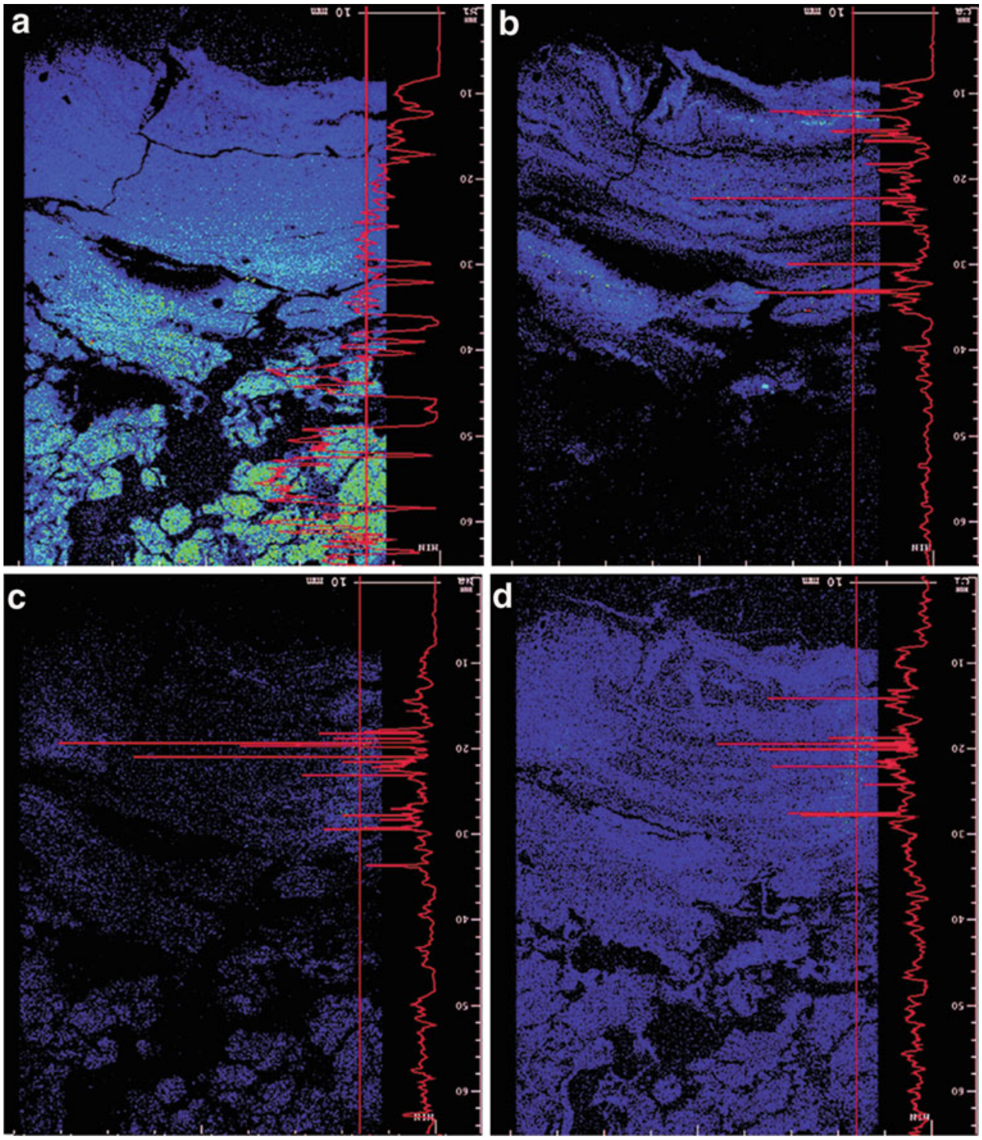


Experimental Geoarchaeology, Figure 1 Wallasea Island, River Crouch, Essex: field photo of Profile 3 dug into a newly marine-flooded grassland soil (after 2 years). Note in the distance the 1953 repaired sea wall breached in 2006 to create new marine wetland. Salt marsh/salt flat sediments are covered in detrital seaweed (see Figure 2).

Experimental Geoarchaeology, Figure 2 Wallasea Island, River Crouch, Essex; flooded Grassland Profile 3; scan of ~11 cm-long resin-impregnated block, showing algae (*A*) coated estuarine clay laminae (*Est*) over buried Ahg and Bg horizons (See Figure 3). (Estuarine clay: 8,950 μmho (micromhos per centimeter) specific conductance: *bAhg*: 4,750 μmho specific conductance).

turf bank from pH 6.9–5.6 (Crowther et al., 1996). The open microfabric (55 % voids) has also diminished to a minimum of 14 % voids at the junction zone between the buried soil and the overlying turf bank, partially through compaction. There was also a change to a spongy microfabric, and broad mammillated earthworm excrements became thinner and more evident of an acidophile mesofauna (soil invertebrates ranging in size between 0.1 mm and 2.0 mm). Less well-drained conditions also developed with the formation of fine ferromanganese nodules, which partially reflected the original humic character of the topsoil. Under the chalk bank, the original decalcified buried soil became biologically mixed with chalk; here, pH rose to 7.9. Bone was patchily preserved in the buried soil, and phosphate migration away from weathering bone was demonstrated. Partially stratified ditch accumulations of chalk and humic soil were presumed to reflect weathering cycles: winter giving rise to stony layers and summer producing fine biologically worked soil. Soil formation on the bank eventually stabilized the bank profile.

The parallel experiment at Wareham, Dorset, (1963) was carried out on acid sandy podzols (typic humod). In the field, the bank remained unstable and rapidly diminished in height, producing berm colluvia, also with infilling of the ditch including turf fragments that had become undercut by ditch side instability. Comparison to control profiles showed no obvious topsoil compaction. The most marked micromorphological change to the buried soil is the thinning of the superficial humus layer (referred to as LFH for litter, fermentation, and humus) from a presumed 70 mm in 1963 to an apparent 50 mm in 1972, which in thin section measurements was found to be 2 mm in 1981 and 1–2 mm in 1996 (Macphail et al., 2003). Oxidation had the effect of "artificially" concentrating the least decomposable organic matter in this buried humus horizon, mainly lignin and charcoal. The lower turf stack held water, and hydromorphic (e.g., iron



Experimental Geoarchaeology, Figure 3 Wallasea Island, River Crouch, Essex; flooded Grassland Profile 3; microprobe maps of Ca, Cl, Na, and Si of thin section across estuarine sediments (marine alluvium) and buried terrestrial soil. This shows the distribution of (**a**) Si, (**b**) Ca, (**c**) Na (which occurs both as saline NaCl salts and as sodium carbonate); and (**d**) Cl. Also note that the terrestrial buried soil is relatively quartz rich (Si), compared to the overlying estuarine alluvium which is more calcitic (Ca). Width of thin section is ~50 mm.

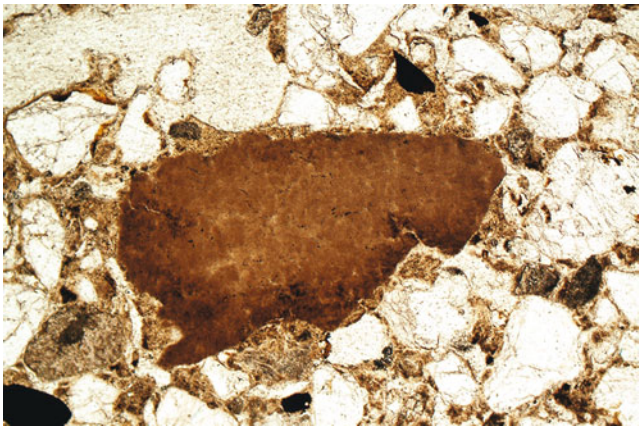
pan) features formed, including the ferrugination of roots, although continued podzolization could also be shown by the marked loss of K but increase in alkali soluble humus and pyrophosphate extractable C. It can also be noted that, at Lejre, Denmark, sandy sods were employed to replicate Iron Age barrow-buried inhumations and were artificially compacted to develop anaerobic conditions; meat, replicating an inhumation, was found to be well preserved over the short term of 3 years (Breuning-Madsen et al., 2001). Other earthwork studies include a series of four octagonal earthworks on four different soil types, instigated by Peter Reynolds (see Butser, below) to monitor bank weathering, ditch infilling, and vegetation invasion as affected by eight different aspects (north facing, south facing, etc.). Recently, the buried soils from Little Butser, Wroughton, Bascomb, and Fishbourne have been examined by Reading University. Fishbourne is on brick earth (loess) over gravels and was 22 years old when excavated (Bell, 2009). As at Overton Down, earthworms had been active in the 16-year-old buried soil on Lower Chalk at Wroughton. All these experimental earthwork findings aid our use of archaeologically buried soils for reconstructing past landscapes and demonstrate how quickly soils may be altered after burial (Crowther et al., 1996; Macphail et al., 2003). Mounds and other earthworks are a universal phenomenon and a global archaeological resource.

In Scandinavia, turf was used for both walls and roofs. At Umeå (Bagböle ancient farm), north Sweden, a 140 mm thick turf roof was made up of two turves upon a roof over a birch bark layer; the basal turf was facedown and the upper turf was faceup, revealing a living grass sward (Macphail and Goldberg, 2010: 279–281). A grass turf (mull Ah horizon/Ap pasture) roof, held together by its root mat, works well if gently pitched, whereas Peter Reynolds at Butser found that a steeply pitched turf roof failed (Reynolds, 1979: 42–43). Moreover, moder (LF), mor (LFH), or peat (histic A) turf roofs do not last, mainly because of organic matter oxidation and lack of living vegetation holding it together (R. Englemark, Umeå, pers. comm.). Pollen and organic matter concentrations show the original way up of turf in mounds (i.e., how it was laid during construction: faceup, facedown, or face-to-face), but at Umeå the topmost, right way up turf (i.e., grassy side upwards) has also the character of a living A1h horizon, with concentrated living roots and excrements of the extant mesofauna. Lime plaster constructions often use calcareous building materials, which are not lime based. Chalk-based cob (a form of daub) on wattle walls, rammed chalk floors, and clunch (crushed chalk adobe-like walls) all show weak cementation of the matrix due to localized recrystallization of calcite, as shown from a clunch-built structure at Butser. In addition to this and "native" British round houses built at Butser, a typical Romano-British villa was reconstructed, based on the Sparsholt Villa, near Winchester. After this building work was completed, heaps of unused constructional materials, including tesserae and mortar, were widespread (Figures 4, 5, 6, and 7). In ancient structures, such spreads may resemble "floors" but are simply constructional waste (Goldberg and Macphail, 2006: Figure 10.4c–d). In experiments, lime plaster and natural calcareous sediments were compared (Karkanas, 2007). Useful ways to identify lime were the recognition of transitional textures of partially carbonized slaked lime (categorized as poorly crystallized portlandite and mixtures of cryptocrystalline calcite). These are found in lime lumps and the matrix cement. A well-developed calcitic groundmass and shrinkage cracks are also possible indicators of lime plasters being present (Karkanas, 2007).

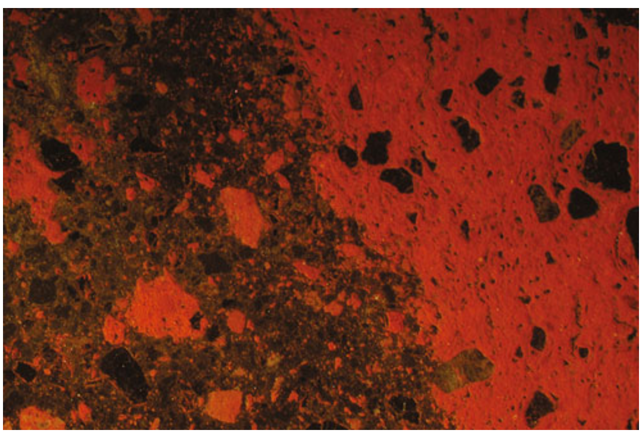
Experimental Geoarchaeology, Figure 4 Butser Experimental Romano-British Farm, Hampshire, UK; reconstructed Roman villa (designed from Sparsholt, near Winchester); a two-storied structure with load-bearing lime mortared flint walls and an upper story which is timber-framed with wattle and daub panels. Walls were lime plastered, floors were either mortared or made up of *opus signinum* to be more hard wearing; here crushed brick or terra-cotta was added to the mortar (see Figures 5, 6, and 7). (http://www.butser.org.uk/bulletin30.html; Christine Shaw, pers. comm).

Disuse and destruction features

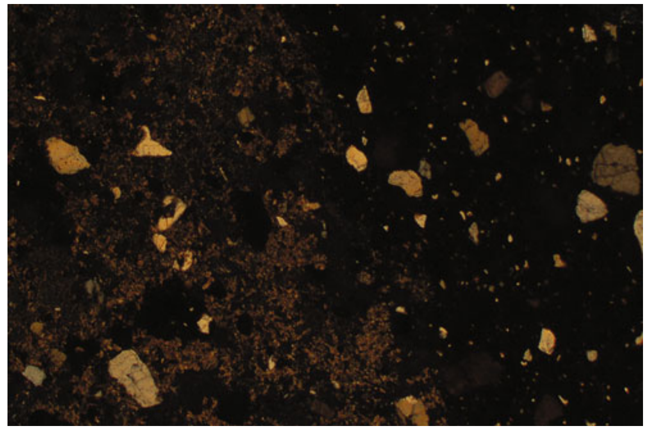
In some cases, it has been possible to see what happens to an "ancient' structure after it has been razed (burned down), a common occurrence in "clay and timber" settlements. At Romano-British Butser Ancient Farm, Hampshire, the thatched *Moel-y-Gaer* roundhouse, which has been used as a stable/byre (see below), was intentionally burned down in 1990, which took only 20 min, as video recorded by Peter Reynolds. The fire generated the highest temperatures by the door lintel, where clay daub was reddened and developed the most enhanced magnetic susceptibility values (Macphail et al., 2004; and P. Reynolds, pers. comm.). Heat from the fire mainly went upwards, and the stable floor showed few effects of heating. Almost immediately afterwards, the daub walls of the house were piled over the old stable floor to attempt to replicate the collapse of walls onto a floor after a fire. A re-excavation in 1995 found the stable floor to be clearly recognizable in terms of its micromorphology and pollen spectrum but that only traces of blue light autofluorescent hydroxyapatite remained (see occupation surfaces, below). In the case of a "pit house" structure at West Stow Anglo-Saxon Village, Suffolk, UK, a likely case of arson(?) led to the "cellar" receiving burned wood debris from the collapsed plank floor, etc., which formed a marked layer in the fill. Constructions of roundhouses at Butser and their dismantlement and reconstruction, during the period ~1975–2010, also showed that so-called drip gullies in the archaeological record could be small mammal runs along the base of the wattle and daub wall and that posts rotted quickly in the ground providing voids into which fills began to develop that reflected roundhouse use (Reynolds, 1995). Use of space studies in longhouses, employing both geoarchaeological and macrobotanical methods, is often based upon the theory that fills are contemporary with the life of the house (Viklund, 1998), as implied at Butser. An experimental house has also been constructed within the site of Çatalhöyük, Turkey (Bell, 2009).



Experimental Geoarchaeology, Figure 5 Butser Experimental Romano-British Farm, Hampshire, UK; reconstructed Sparsholt Roman villa; photomicrograph of constructional debris spreads: mortar. Here, a lime mortar binder has been tempered with medium sand (used to cement coarse flint walls in the villa); mortar includes incompletely burned chalk ($CaCO_3$), as a residue from lime (quicklime CaO) making in a kiln at ~1,000 °C (Reference material kindly supplied by Christine Shaw) Plane polarized light, frame width is ~2.38 mm.



Experimental Geoarchaeology, Figure 6 Butser Experimental Romano-British Farm, Hampshire, UK; reconstructed Sparsholt Roman villa; photomicrograph of constructional debris spreads: *opus signinum*. In order to produce a hard-wearing mortar, crushed brick (*red material*) was added to mortar; the precipitation of aluminum silicates from the brick into the mortar binder creates a more robust mortar. Note coarse and finely fragmented red brick material (Reference material kindly supplied by Christine Shaw) Oblique incident light, frame width is ~4.62 mm.



Experimental Geoarchaeology, Figure 7 Butser Experimental Romano-British Farm, Hampshire, UK; reconstructed Sparsholt Roman villa; photomicrograph of constructional debris spreads: *opus signinum*. Same as Figure 6, now under cross-polarized light (XPL). Brick is isotropic (appears dark) under XPL, whereas the calcium carbonate lime mortar is birefringent (transmits double refracted light).

Activities, features, and materials

Fires, ovens, and furnaces

Many experiments have been undertaken to replicate activities, such as surface camp fires (Linford and Canti, 2001), iron working, and smithing in the field of experimental archaeometry. Some diagnostic mineral magnetic properties develop in the soils and ash of camp fires, but they vary according to depth, nature of the substrate, and length of heating time. A few studies have been focused upon the geoarchaeology of ovens, hearths, and furnaces. The large ("Pimperne") roundhouse at Butser has a clay oven constructed from daub (straw and dung-tempered clay loam soil). In thin section, some iron clays had become rubified (reddened) while organic materials had often become lost (oxidized) or blackened. In a straw-tempered, rubified chalky clay oven replicating Roman and Saxon installations at West Heslerton, North Yorkshire, the presence of blackened straw sections suggests that temperatures remained moderately low (~<400 °C), because barley straw has been found to oxidize around this temperature (Dammers and Joergensen, 1996; Macphail, 2002; Macphail and Goldberg, 2010: Figure 6). Another effect is the shrinking of the fine matrix around the straw, and fissuring in general, due to loss of water from the clay. At higher temperatures, mineralogical changes identified by FTIR (fourier transform infrared) spectrometry have been found in experimental furnaces using bellows (Berna et al., 2007) (Table 1).

When such transformed minerals are found in archaeological deposits, it is therefore logical to infer that they arise from local "industrial" activities.

Animal management

A classic experiment in soil science concerning the compacting effects of animal trampling was carried out using a mechanical foot loaded to 138 kPa (~1.45 psi) in Queensland, Australia, to examine changes in rainfall acceptance by different soil types and how trampling

Experimental Geoarchaeology, Table 1 The effect of increasing temperature on minerogenic materials in ovens and furnaces (From Berna et al., 2007)

Temperature	Effect
Up to 400 °C	Reddened sediment with unaltered clay components
500–700 °C	Loss of kaolinite, dehydroxylation, and partial vitrification of smectite
800–900 °C	Quartz with residual altered clay minerals
1,000–1,200 °C	"Altered quartz," opal, tridymite
1,300 °C and above	Glaze-like phase, cristobalite

Experimental Geoarchaeology, Figure 8 Butser Experimental Romano-British Farm, Hampshire, UK; field photo of the Reynolds team using two Dexter cattle to pull an Iron Age replica ard (scratch plough) in one of the arable fields in the "old demonstration area" (1972–1990) (Photo kindly supplied by Peter Reynolds).

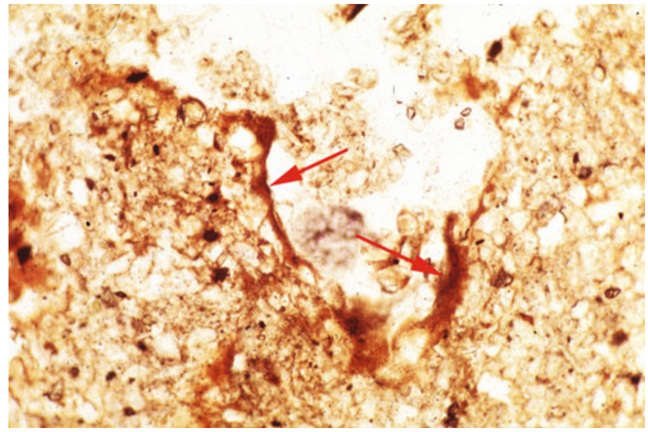
altered this (Beckman and Smith, 1974). All soil types lost structure, with even clayey, stable well-structured soil suffering surface collapse and development of a comparatively impermeable "skin." Aggregates in soils that began as apedal and massive in character totally collapsed and developed densely packed surface layers, and additional wetting and trampling had no further effect. This is the kind of phenomenon found in muddy trackways, for example. Pounding or stocking of domestic animals can have the same effects, although pig husbandry (below) is a special case which has been investigated.

An experimental "pig pasture" at the Lann-Gouh "medieval" farm near Melrand, Morbihan, Brittany, in northwestern France was investigated (Gebhardt, 1995). Here, pigs ("Porcs de Bayeaux") quickly disturbed soil surfaces and uprooted some small trees in an open-forested area. The chief result of pig action was to create a 150 m-thick compacted colluvium composed of mixed Ao and A1 soil and fragments of B horizon. This buried the in situ forest soil formed on a granitic parent material. This study was followed up in the UK (Macphail and Crowther, 2011) by examining both the "pig pasture" and small adjoining pig enclosure area at West Stow Anglo-Saxon Village, Suffolk, UK, on Breckland sands (see below for stabling of cattle, sheep, and goats). In 2008, two pigs (cross-bred Tamworths) occupied a small enclosure where their pathways to drinking water showed concentrations of fecal remains. The "pig pasture" showed churning and mixing of the sandy Ah and clean sands from the A2 horizon. Bulk sample chemistry located the highest concentrations of organic matter and phosphate in an example of the pig-trampled and dung-enriched crust of the pathway surface in the small enclosure. The surface crust was compact and composed of a concentration of sub-horizontally layered, partially digested, cereal husk remains and amorphous organic matter (pig fecal waste). Scanning electron microscope/energy-dispersive spectrometry analyses found the phosphate to be concentrated in these fecal remains, alongside iron, calcium, and sulfur. Below this crust layer, nodules of amorphous iron, phosphorus, and calcium were present and logically so are neo-formed features of pig slurry origin developed over several years of keeping pigs here. The concept of equifinality has always to be borne in mind, however, similar results can emerge from several possible scenarios in such experiments, which are not laboratory controlled.

Cultivation

Much of our understanding of ancient cultivation has been achieved by extrapolating findings from modern agronomy. This database, however, has not always been sufficient because modern cultivation regimes and heavy machinery are so unlike past methods. Still, it has been useful, for example, in the study of crusts forming on bare arable soils due to rainsplash (McIntyre, 1958; Boiffin and Bresson, 1987). Experiments in *ancient* agriculture have been criticized on the basis that they have taken place on modern soils and even in "soil bins" (Silsoe Agricultural College, Bedfordshire, UK; Lewis, 2012), but to find a *totally* undisturbed soil of early Holocene origin may be impossible. Like any experiment, constraints have to be built into the interpretation of the resulting data. An interesting suite of soil types and cultivation methods was analyzed during the late 1980s from two French (Déherain and Grignon experimental farms), one German (Hambacher Forst), and one UK site (Butser) and then compared to supposed archaeological examples (Macphail et al., 1990; Gebhardt, 1992) (Figures 8, 9, and 10). At Hambacher Forst, a replica Neolithic ard plough was used to cultivate between trees on loess soils (Meurers-Balke, 1985). In all cases, cultivation led to soils becoming looser through an "explosion" of fine structures, which was believed to relate to the inherent weakness of soil structures caused by wetting and drying. These weaknesses fractured under tool impact, a phenomenon known from modern plowing – in part carried out to develop a fine tilth suitable for rooting. Gebhardt found that

Experimental Geoarchaeology, Figure 9 Hambacher Forst, Rhinelands, Germany; field photo of "Neolithic" ard plowing by Meurers-Balke and her team (Cologne University) during 1985; they carried out cross plowing in woodland on loess soils. (Photo kindly supplied by Anne Gebhardt).



Experimental Geoarchaeology, Figure 10 Hambacher Forst, Rhinelands, Germany, "Neolithic" ard-plowed loess soil; photomicrograph of junction between newly formed Ap topsoil and subsoil A2 horizon formed in loess silt. Note dusty clay void coatings and concentrations (*arrows*), which may possibly direct result from this plowing experiment. (Thin section kindly loaned by Anne Gebhardt) Plane polarized light, frame width is ~3.3 mm.

resulting ped size could be associated with tool type, with medium angular peds at Butser (ard) and coarse angular peds at Déherain (spade). At all sites, the nature of the uncultivated soil could be ascertained from the inclusion of recognizable humic soil within the clods, and numbers of peds increased, although at Hambacher Forest this was less obvious because of poor structural stability. Soil horizon mixing (topsoil and subsoil) was, however, clearly obvious here. Peds were also compacted into loose soil in this weakly structured soil, with a 1 cm thick silt pan forming at a depth of ~6 cm, and at 12–14 cm some dusty clay had accumulated over a limpid clay of assumed woodland soil origin that had presumably formed earlier. Excessive watering at Grignon Forest caused structural collapse and the formation of bird's foot-/star-shaped voids (cf. polyconcave voids) as evidence of this. Further sampling of Butser manured and non-manured arable soils and control, non-cultivated surface horizons, was carried out in 1990; organic matter and phosphate were also measured (Macphail, et al., 2004). Structural stability was well maintained here (the 1990 Old Demonstration Area) because of the high base status of the soils (calcareous colluvium) and high organic content; organic matter levels actually rose despite cropping, and although no erosion was noted, fields became dish shaped (Reynolds, 1987; Reynolds, pers. comm.).

Anne Gebhardt's studies were followed up by those of Helen Lewis who, for example, examined experimentally cultivated soils from the Little Butser downland site and Lejre Museum (west of Copenhagen, Denmark). In addition, Neolithic (Donneruplund) ard cultivation was carried out on artificial fine sandy loams in soil bins at Silsoe, Bedfordshire, UK (Lewis, 2012). Some results are:

- The shape of the furrow varies according the share used; the arrow-shaped share produced a wide V-shaped furrow; a rounded U-shaped furrow was made when only the main straight share was employed.
- Furrows were 60–70 to 120–150 mm in depth and 210–220 mm wide.

A number of zones were identified in the plough soil, with different characteristics; these are:

- "Ridge" (e.g., blocks and aggregates formed from the original apedal soil)
- Furrow upper fills (e.g., rolled aggregates over apedal soil)
- Furrow basal fills (e.g., lines of fine soil and fine aggregates follow line of cut)
- Furrow cut (e.g., arrow-shaped share produces stepped profile with changes in soil density, becoming more compact downwards)
- Furrow compaction/impact zone (e.g., planar voids run-off at 90°; dense soil zone 10 mm under furrow)
- Sub-furrow compaction/impact zone (e.g., planar voids mirror base of furrow for 10–40 mm)

These soil bin experiments were protected from the weather, but at Lejre and Butser, textural pedofeatures had formed due to soil water dispersion.

As at Butser, where the chief aim was to grow ancient crops (and associated weeds), cultivation of Boreal podzols (ferrods) at Baggböle Farm, Umeå (north Sweden), tested the sustainability of slash-and-burn versus manured cultivation for the growing of barley during the Iron Age (Viklund, 1998). Slash and burn had a very ephemeral effect on pine woodland, with the surface 30 mm becoming characterized by an "anomalous" concentration of fine to coarse pine wood charcoal and by the presence of thin to

Experimental Geoarchaeology, Table 2 Experimental floors, stables, and domestic space: a summary of characteristics at Butser Ancient Farm 1975–1990 (After Goldberg and Macphail, 2006, Tables 12.2–12.3)

Stable floors	Typically homogeneous where high concentrations of organic matter, phosphate, and pollen grains may be preserved. Organic matter occurs in the form of layered plant fragments which, depending on pH, are either cemented (e.g., hydroxyapatite) or stained by phosphate. If preservation conditions permit the survival of pollen grains, they are likely to be abundant and possibly highly anomalous with respect to the surrounding area	Butser surface crust: 40.9 % LOI (loss on ignition), 5,960 ppm P, $\chi = 27\ (\times 10^{-8}\ m^3\ kg^{-1})$
Domestic floors	Typically heterogeneous; floor deposits are comparatively mineralogenic, massive structured, and contain abundant anthropogenic and allocthonous inclusions, such as burned soil, charcoal, and ash. Plant fragments are less common and may occur in single layers of organic mat remains. The palynology of domestic floors is an under-investigated subject, but available data suggest the likelihood of far more diverse weed pollen assemblages (reflective of settlement flora), lower concentrations and poorer preservation than in stabling deposits. Magnetic susceptibility is likely to be enhanced and P and LOI will reflect in situ activities and trampled-in materials	Butser beaten surface: 20.2 % LOI, 2,430 ppm P, $\chi = 47\ (\times 10^{-8}\ m^3\ kg^{-1})$

moderately broad (200–1,000 μm) mesoaggregated excrements of invertebrate mesofauna (Macphail, 1998). These occur in addition to the very thin and moderately thin (50–200 μm) excrements that dominate the L/F and Ah horizons of the local pine-covered podzols. This larger-size excrement type reflects the, albeit short lived, improved fertility of the slash-and-burn podzol. The chief characteristic of the permanently manured cultivated soil, which had the highest concentrations of organic matter and phosphate at the Baggböle Farm (Goldberg and Macphail, 2006: Table 12.4), was the total homogenization of the L, F, Ah, and A2 horizons into an Ap horizon that reached as far as the Bs horizon (these near coastal soils are shallow because of recent exposure ~2,000 bp due to postglacial uplift). Charcoal and other anthropogenic inclusions and exotic materials (e.g., limestone, pottery) were present throughout, along with individual fragments of dung, up to ~5 mm in size. The occurrence of iron pan fragments testified to cultivation affecting the spodic subsoil. Levels of biological activity were enhanced with thin to moderately broad organo-mineral excrements throughout. This is consistent with the transformation of superficial humus (L, F, H), Ah, and A2 horizons of podzols into overdeepened Ap horizons of plaggen soils which are characterized by a "moder" humus.

Occupation Floors and Use of Internal Space

The chief studies of how experimental domestic and stabling (byre) floors differ, again, took place at Butser. They first involved the 1975–1990 sites: the small *Moel-y-Gaer* roundhouse used to house stock over the winter and the large domestic *Pimperne* roundhouse, as reconstructed from Iron Age archaeological site evidence (Reynolds, 1979). The large roundhouse was built in 1992 as a Longbridge-Deverel (Cowdown, Wiltshire) reconstruction. As soon as the roof went on, the grass died, and the formation of a "beaten floor" commenced (Reynolds, pers. comm.). Chemical, pollen, and micromorphological analyses were carried out on the Moel-y-Gaer and Pimperne floors in order to see how the very different functions of space were represented by the resulting floor accumulations (Tables 2 and 3) (Macphail and Cruise, 2001; Macphail et al., 2004).

Comparisons to numerous occupation floor deposits in archaeological sites are consistent with these experimental findings, although domestic floors can show higher phosphate concentrations because of food disposal and latrine waste spillage, something not conducive to modern "health and safety" at open-air museums. Nevertheless, the results from the Pimperne house floor demonstrate traffic within the house and traffic into the house, bringing in soil and organic matter from outside. Such cyclical deposition is common to beaten floors. It can be noted that when the 1992 Longbridge-Deverel house floor was sampled in 1994, both locations (rear and main area) showed immaturity of development compared to the much longer lived Pimperne house, for instance, with only 12 % LOI (loss on ignition) and 1360–1880 ppm P % levels (Macphail et al., 2006). Further floor samples were collected from the next domestic roundhouse incarnation in ~2005, but floor deposits were no longer accumulating through traffic but being lost because pathways had now been graveled (unlike ancient conditions). Floor soil now had to be replaced and compacted as a repair and thus no longer reflected an actual traffic-accumulated beaten floor.

Summary

This entry provides some examples of geoarchaeological experiments sensu lato; these, together with ethnographic and archaeological case studies, have successfully advanced our understanding of cultures as found in the soil and sediment record at archaeological sites. First, experiments involving pedology, geomorphology, and the biological sciences have aided our understanding of natural processes. Constructions, settlement morphology, and use of space, however, cannot be understood properly by simply relying on the natural sciences. Instead, specific experiments (turf-based earthworks, lime making, ovens) have had to be carried out. In addition, many advances have been made from the careful use of material from open-air museums and ancient farm and settlement

Experimental Geoarchaeology, Table 3 Immature beaten domestic floor soils; Butser Longbridge Deverel roundhouse 1992–1994

Depth (m)	LOI (%)	P (ppm)
Beaten floor (main area)		
0–0.005 m	12.0	1,360
0.005–0.04 m	8.5	1,220
0.04–0.08 m	8.1	1,240
Beaten floor (wall corridor)		
0–0.005 m	12.0	1,880
0.005–0.04 m	8.7	1,270
0.04–0.08 m	8.1	1,290

reconstructions. Management of these institutions, however, governs how useful these can be for replicating archaeological site formation processes. Notably, the regime at Butser Ancient Farm under Peter Reynolds during the period 1972–1990 produced an unrivalled environment for studying "Iron Age" cultivated soils and domestic and stabling floors formed in roundhouses.

Bibliography

Beckman, G. G., and Smith, K. J., 1974. Micromorphological changes in surface soils following wetting, drying and trampling. In Rutherford, G. K. (ed.), *Soil Microscopy*. Kingston: The Limestone Press, pp. 832–845.

Bell, M., 2009. Experimental archaeology: changing science agendas and perceptual perspectives. In Allen, M. J., Sharples, N. M., and O'Connor, T. (eds.), *Land and People: Papers in Memory of John G. Evans*. London: Prehistoric Society, pp. 31–45.

Bell, M., Fowler, P. J., and Hillson, S. W., 1996. *The Experimental Earthwork Project, 1960–1992*. York: Council for British Archaeology.

Berna, F., Behar, A., Shahack-Gross, R., Berg, J., Boaretto, E., Gilboa, A., Sharon, I., Shalev, S., Shilstein, S., Yahalom-Mack, N., Zorn, J. R., and Weiner, S., 2007. Sediments exposed to high temperatures: reconstructing pyrotechnological processes in Late Bronze Age and Iron Age strata at Tel Dor (Israel). *Journal of Archaeological Science*, **34**(3), 358–373.

Boiffin, J., and Bresson, L. M., 1987. Dynamique de formation des croutes superficielles: apport de l'analyse microscopique. In Fedoroff, N., Bresson, L. M., and Courty, M.-A. (eds.), *Soil Micromorphology*. Plaisir: Association Française pour l'Étude du Sol, pp. 393–399.

Breuning-Madsen, H., Holst, M. K., and Rasmussen, M., 2001. The chemical environment in a burial mound shortly after construction – an archaeological-pedological experiment. *Journal of Archaeological Science*, **28**(7), 691–697.

Crowther, J., Macphail, R. I., and Cruise, G. M., 1996. Short-term post-burial change in a humic rendzina soil, overton down experimental earthwork, Wiltshire, England. *Geoarchaeology*, **11**(2), 95–117.

Dammers, K., and Joergensen, R. G., 1996. Progressive loss of carbon and nitrogen from simulated daub on heating. *Journal of Archaeological Science*, **23**(5), 639–648.

Farres, P. J., Wood, S. J., and Seeliger, S., 1992. A conceptual model of soil deposition and its implications for environmental reconstruction. In Bell, M., and Boardman, J. (eds.), *Past and Present Soil Erosion: Archaeological and Geographical Perspectives*. Oxford: Oxbow. Oxbow Monograph, Vol. 22, pp. 217–226.

Ferrick, M. G., and Gatto, L. W., 2004. *Quantifying the Effect of a - Freeze-Thaw Cycle on Soil Erosion, Laboratory Experiments*. Hanover: Ft. Belvoir Defense Technical Information Center, Cold Regions Research and Engineering Laboratory.

Gebhardt, A., 1992. Micromorphological analysis of soil structural modification caused by different cultivation implements. In Anderson, P. C. (ed.), *Préhistoire de l'agriculture: nouvelles approaches experimentales et ethnographiques*. Paris: Éditions du Centre Nationale de la Recherche Scientifique. Monographie de CRA No. 6, pp. 373–392.

Gebhardt, A., 1995. Soil micromorphological data from traditional and experimental agriculture. In Barham, A. J., and Macphail, R. I. (eds.), *Archaeological Sediments and Soils: Analysis, Interpretation and Management*. London: Institute of Archaeology, pp. 25–40.

Goldberg, P., and Macphail, R. I., 2006. *Practical and Theoretical Geoarchaeology*. Oxford: Blackwell Publishing.

Karkanas, P., 2007. Identification of lime plaster in prehistory using petrographic methods: a review and reconsideration of the data on the basis of experimental and case studies. *Geoarchaeology*, **22**(7), 775–796.

Lewis, H., 2012. *Investigating Ancient Tillage: An Experimental and Soil Micromorphological Study*. Oxford: Archaeopress. British Archaeological Reports, International Series, Vol. 2388.

Linford, N. T., and Canti, M. G., 2001. Geophysical evidence for fires in antiquity: preliminary results from an experimental study. Paper given at the EGS XXIV general assembly in The Hague, April 1999. *Archaeological Prospection*, **8**(4), 211–225.

Macphail, R. I., 1998. A reply to carter and Davidson's "an evaluation of the contribution of soil micromorphology to the study of ancient arable agriculture". *Geoarchaeology*, **13**(6), 549–564.

Macphail, R. I., 2002. Industrial activities – some suggested microstratigraphic signatures: ochre, building materials and iron-working. In Wiltshire, P. E. J., and Murphy, P. (eds.), *The Environmental Archaeology of Industry*. Oxford: Oxbow. Symposia of the Association for Environmental Archaeology, Vol. 20, pp. 94–106.

Macphail, R. I., and Crowther, J., 2011. Experimental pig husbandry: Soil studies from West Stow Anglo-Saxon Village, Suffolk, UK. *Antiquity Project Gallery*, **85**(330): http://antiquity.ac.uk/projgall/macphail/.

Macphail, R. I., and Cruise, G. M., 2001. The soil micromorphologist as team player: a multianalytical approach to the study of European microstratigraphy. In Goldberg, P., Holliday, V., and Ferring, R. (eds.), *Earth Science and Archaeology*. New York: Kluwer Academic/Plenum Publishers, pp. 241–267.

Macphail, R. I., and Goldberg, P., 2010. Archaeological materials. In Stoops, G., Marcelino, V., and Mees, F. (eds.), *Interpretation of Micromorphological Features of Soils and Regoliths*. Amsterdam: Elsevier, pp. 589–622.

Macphail, R. I., Courty, M. A., and Gebhardt, A., 1990. Soil micromorphological evidence of early agriculture in north-west Europe. *World Archaeology*, **22**(1), 53–69.

Macphail, R. I., Crowther, J., Acott, T. G., Bell, M. G., and Cruise, G. M., 2003. The experimental earthwork at Wareham, Dorset after 33 years: changes to the buried LFH and Ah horizon. *Journal of Archaeological Science*, **30**(1), 77–93.

Macphail, R. I., Cruise, G. M., Allen, M. J., Linderholm, J., and Reynolds, P., 2004. Archaeological soil and pollen analysis of experimental floor deposits; with special reference to Butser Ancient Farm, Hampshire, UK. *Journal of Archaeological Science*, **31**(2), 175–191.

Macphail, R. I., Cruise, G. M., Allen, M. J., and Linderholm, J., 2006. A rebuttal of the views expressed in "Problems of unscientific method and approach in 'archaeological soil and pollen analysis of experimental floor deposits; with special reference to Butser Ancient Farm, Hampshire, UK' by R. I. Macphail, G.M. Cruise, M. Allen, J. Linderholm and P. Reynolds" by Matthew Canti, Stephen Carter, Donald Davidson and Susan Limbrey. *Journal of Archaeological Science*, **33**(2), 299–305.

Macphail, R. I., Allen, M. J., Crowther, J., Cruise, G. M., and Whittaker, J. E., 2010. Marine inundation: effects on archaeological features, materials, sediments and soils. *Quaternary International*, **214**(1–2), 44–55.

McIntyre, D. S., 1958. Soil splash and the formation of surface crusts by raindrop impact. *Soil Science*, **85**(5), 261–266.

Meurers-Balke, J., 1985. Experimente zum Anbau und zur Verarbeiterung prähistorischer Getreidearten. *Archäologische Informationen*, **8**(1), 8–17.

Mücher, H. J., and Morozova, T. D., 1983. The application of soil micromorphology in quaternary geology and geomorphology. In Bullock, P., and Murphy, C. P. (eds.), *Soil Micromorphology*. Berkhamsted: AB Academic Publishers, pp. 151–194.

Reynolds, P., 1979. *Iron Age Farm: The Butser Experiment*. London: British Museum Publications.

Reynolds, P., 1987. *Ancient Farming*. Aylesbury: Shire Publications. Shire Archaeology, Vol. 50.

Reynolds, P., 1995. The life and death of a post-hole. In Shepherd, E. (ed.), *Interpreting Stratigraphy 5, Proceedings of a Conference held at Norwich Castle Museum on 16th June 1994*. Bawdeswell: Interpreting Stratigraphy, pp. 21–25.

Viklund, K., 1998. *Cereals, Weeds and Crop Processing in Iron Age Sweden. Methodological and Interpretive Aspects of Archaeobotanical Evidence*. Umeå: University of Umeå, Department of Archaeology, Environmental Archaeology Laboratory. Archaeology and Environment, Vol. 14.

Cross-references

Boxgrove
Fourier Transform Infrared Spectroscopy (FTIR)
House Pits and Grubenhäuser
Pastoral Sites
Scanning Electron Microscopy (SEM)

F

FIELD GEOCHEMISTRY

Richard E. Terry
Plant and Wildlife Sciences Department, Brigham Young University, Provo, UT, USA

Definition

Geochemical analysis: The chemical analysis of elements associated with soils, rocks, and minerals.

Ethnoarchaeology: The application of archaeological techniques to elucidate contemporary human activities.

Chelate: Complex organic molecules that surround metallic ions to hold them in solution and prevent their chemical precipitation.

Introduction

Examinations of the physical and chemical properties of soils produce data that augment archaeological information on the structures and artifacts left behind by ancient peoples. In fact, the soil is a *palimpsest* of the physical changes and chemical residues associated with both ancient and contemporary human activities on the land surface. The origin of the term palimpsest dates to classical times, but it commonly refers to medieval manuscripts on parchment that were reused, because the medium was valuable and more durable than papyrus or paper. The old ink was partially effaced to clear the sheet for new writing, and in most cases, vestiges of the previous text, though faded and indistinct, could still be discerned. This aptly describes the soil medium as a cumulative recorder of human activities from ancient to contemporary times (Bailey, 2007; Dore and López Varela, 2010). Soils can store pollen, phytoliths, bones, architectural components, and nonperishable artifacts over sequential occupations; however, perishable organic implements and food that are readily decomposed and seldom survive to become part of the artifactual record may have initially accounted for as much as 90 % of an ancient household's artifact inventory (Cavanagh et al., 1988; Dahlin et al., 2007). Such organic materials associated with food preparation and consumption can lose their carbon and nitrogen components, which decompose to gaseous and soluble substances, yet phosphorus (P) and certain trace nutrients – including iron (Fe), copper (Cu), manganese (Mn), and zinc (Zn) – are adsorbed onto soil particles or are precipitated as insoluble compounds and remain for centuries at the location of ancient use. These and other geochemical residues of human activities serve as invisible artifacts.

Nonperishable artifacts associated with abandoned habitations and public structures were often picked up and moved and then reused at distant locations. In most cases, the soils and earthen floors of former landscapes are not transported, and thus the geochemical residues within soils provide excellent in situ evidence of ancient use (Barba et al., 1996; Wells et al., 2000; Parnell et al., 2001; Parnell et al., 2002; Barba, 2007). Geochemical analyses of soils and floors have become established archaeological methods for locating ancient sites. The results further define the types and extent of human activities within those sites and help in the interpretation of those activities (see reviews by Wilson et al., 2005; Wilson et al., 2006; Holliday and Gartner, 2007; Walkington, 2010).

Anthropogenic chemical residues in soils

Phosphorus (P)

The application of phosphate analysis in archaeology was first developed in Europe in the 1930s, where pioneering efforts by Arrhenius (1931) and Lorch (1940) indicated that areas of ancient occupation contained elevated

A.S. Gilbert (ed.), *Encyclopedia of Geoarchaeology*, DOI 10.1007/978-1-4020-4409-0,

concentrations of soil P. Ethnographic studies likewise illustrated the relationship of P concentration with domestic activities (Barba and Ortiz, 1992; Middleton and Price, 1996; Fernández et al., 2002; Terry et al., 2004). Phosphorus is used by plant and animal cells in plasma membranes, nucleic acids, and other organic molecules. When ancient plant and animal foodstuffs were harvested and brought into dwelling places, the P contained in the food was also introduced into the settlement. As the food waste decomposed, the mineralized P was readily fixed onto the surface of soil particles and remained stable for long periods of time (Barba and Ortiz, 1992; Holliday and Gartner, 2007). Activities such as preparation, storage, and disposal of food as well as the fertilizing of soil for agriculture have left distinct chemical residues that remain relatively in their original place within the soil for centuries.

Soil samples collected prior to excavation can be analyzed and their chemical patterns determined and mapped, in order to prospect for archaeological features of interest. For instance, Parnell et al. (2001) reported a significant positive correlation between sherd density discovered within test pits and surface soil P concentrations. An area that contains elevated soil P near architectural structures may indicate locations of residential middens.

Floors with elevated P concentrations may indicate kitchen and food consumption areas. Ethnoarchaeological studies of indigenous households have demonstrated that activities associated with high soil P concentrations include gardening, food preparation, waste disposal, and sweeping that pushes organic material to the peripheries of patios and high-traffic areas (Barba and Ortiz, 1992; Fernández et al., 2002). Combined with other lines of evidence, geochemical data have helped identify areas used as sleeping quarters and spaces in which ritual and funerary activities were conducted (Barba et al., 1995; de Pierrebourg, 1999). Thus, extraordinarily high P concentrations in soils and on floors can be associated with prehistoric food preparation, consumption, storage, and disposal. Very low levels of P could indicate high-traffic areas such as pathways and patio centers, as movement and sweeping push organic debris to the outer margins.

Several methods of P extraction have been used in geochemical studies of ancient activity areas. Dilute acid extraction procedures remove a portion of the P adsorbed onto the surfaces of soil particles (e.g., Mehlich, 1978; Middleton and Price, 1996; Terry et al., 2000; Rypkema et al., 2007). The concentrations of extracted P vary with the type and strength of the acid. In each extraction procedure, the portion of P analyzed is affected by soil acidity or alkalinity, percentage of organic matter, clay content and mineralogy, and other physical and chemical properties of the soil. For these reasons, the magnitude of extracted P concentration differs with the extraction procedure, with the type of soil, and with the geographic origin of the soil.

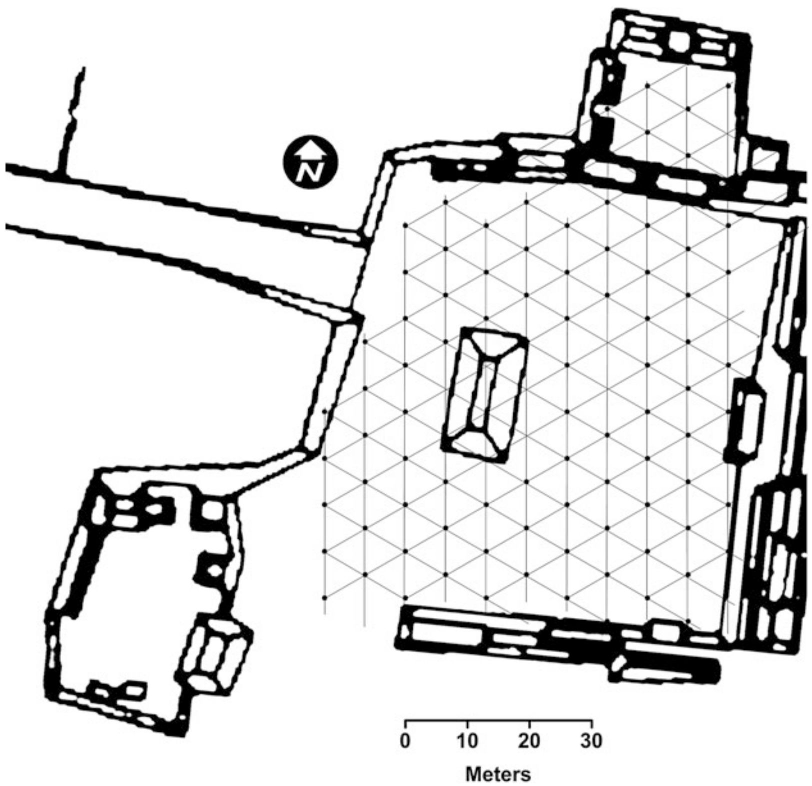
Trace elements

Anthropogenic metal and trace element residues have proven useful in the identification of ancient activities. Much of this work has focused on Cu, Fe, Mn, lead (Pb), and Zn (Bintliff et al., 1990; Entwistle and Abrahams, 1997; Entwistle et al., 1998; Entwistle et al., 2000; Parnell et al., 2002; Terry et al., 2004). Many of the metallic ions remain stable in soils for long periods, as their ions are readily adsorbed and precipitated onto clay surfaces, and they can form insoluble oxides, sulfates, or carbonates (Lindsay, 1979; Wells et al., 2000). Some pigments and paints used by the pre-Hispanic Maya contained metallic bases, such as hematite and cinnabar (Goffer, 1980; Vázquez Negrete and Velázquez, 1996a; Vázquez Negrete and Velázquez, 1996b), and thus, elevated values of trace metals in soils may help to identify areas where pigments were processed or applied and where craft workshops were located (Terry et al., 2004). For example, evidence of workshop activities was provided by trace metal extraction and inductively coupled plasma mass spectrometry (ICP/MS) or atomic emission spectroscopy (ICP-AES) analyses of soil and floor samples at Cancuén (Cook et al., 2006), Piedras Negras, and Aguateca, Guatemala (Parnell et al., 2002; Terry et al., 2004). Multivariate analysis of P and several trace metals has also proven useful (Parnell et al., 2002; Abrahams et al., 2010; López Varela and Dore, 2010).

Geochemical analysis in the field

Two problems arise when samples must be delivered from the field to a distant formal laboratory setting with the attendant lengthy wait for chemical analysis and data processing. First, the process of moving samples from field to laboratory and the analytical time required at a busy soil laboratory mean that geochemical data are usually not available before the end of the field season. Second, the permitting process for carrying soil samples across international borders is time-consuming and often both difficult and expensive. For these reasons, archaeological prospection benefits greatly from more rapidly obtained results from analyses conducted in situ and in a field laboratory. As geochemical techniques in archaeological research have developed and as analytical capabilities have advanced, the demand has grown for relatively quick data obtained at the time of excavation or at least in a field laboratory so that within minutes or a couple of days, results can be available to guide archaeological investigations and to target features of interest.

Simple spot tests for soil P, amino acids, and lipids have been developed (Eidt, 1973; Barba et al., 1991) for in situ use. In the field laboratory, extractable P tests can be conducted with relatively inexpensive equipment and chemicals. Both Terry et al. (2000) and Rypkema et al. (2007) have described such tests and equipment. Much of the equipment needed for geochemical analysis of archaeological soils in a field laboratory is available



Field Geochemistry, Figure 1 A triangular grid was superimposed on the Conchita Plaza group near Caracol, Belize. Each grid point was 10 m from adjacent grid points. North-south pathways through the dense vegetation were cut 8.67 m apart to allow equidistance sampling at 10 m.

in battery-powered form, including electronic balances, timers, pH meters, and colorimeters. Deionization cartridges can be linked by flexible tubing in the field lab to provide laboratory-quality water for chemical analyses.

Limitations inherent in a field laboratory setting likely preclude the use of concentrated acids for sample digestion in preparation for total elemental analysis. There are the safety issues of toxic fumes and the necessity of safety showers, eyewashes, and climate control that are cost prohibitive in a field laboratory situation. In addition, the inductively coupled plasma (ICP) spectrometer and the atomic adsorption (AA) spectrophotometer necessary for total element analysis are not available in a format that would allow field laboratory use. However, recent advances in the development of battery-operated, portable X-ray fluorescence (pXRF) instruments may allow researchers to obtain reliable total elemental analysis both in situ and in the field laboratory.

Soil sampling

The key to excellent soil geochemical data is representative and statistically sound sampling. Only a few crumbs or a couple of grams of soil end up in an extraction vessel or an analysis vial. Those tiny amounts of soil must therefore adequately represent the specific area of sampling. Samples may be taken on a gridded system for geospatial analysis of an area, or they may be taken at intervals along a transect in search of "hot spots" for later study. In many cases, the ancient occupation surface is at the contemporary soil surface. Leaf litter should be removed and approximately 500 g of soil collected. It is recommended that this sample be obtained from three or four spots within 0.5 m of a grid point or transect location. The sample contains moisture, roots, and gravel that should be removed during sample preparation. It is important to collect sufficient sample for all of the planned analyses, along with sufficient sample to allow procedures to be repeated if necessary. In some cases, excavated occupation surfaces are exposed and lend themselves well to sampling. The archaeologist's grid can help in the sampling. If there are no excavation markers, a permanent reference point with east-west and north-south lines can establish a grid. Geospatial analysis is most effectively conducted if the distance between adjacent samples is the same, and this can be facilitated with an isosceles triangular grid (Figure 1).

The type of sampling bag to be used should be carefully considered. In either the field lab or the formal laboratory setting, the analyst is going to remove either the full contents or only part of the material repeatedly. We have found heavy (0.064 mm thick) plastic bags to work best if they must be opened and closed several times. Sandwich bags or light-duty plastic bags tend to leak, they do not stand up, they do not facilitate vigorous mixing, and they generally do not survive a bank of soil preparation and analysis procedures.

Soil sample preparation

For geochemical concentration data to be accurate, soil samples need to be air-dried, crushed, and sieved to remove rocks, roots, and non-soil debris. Soil samples should be corrected for air-dry moisture content, which can be done by weighing the sample and oven-drying it at approximately 105 °C to constant weight (generally 12–24 h depending on size of the sample). The field lab is unlikely to have access to a drying oven; therefore, upon return to the formal laboratory, the air-dry and oven-dry weights should be determined so that moisture correction factors can then be applied.

In a field lab, a few mortars and pestles can facilitate crushing of dry soil aggregates, using care so as not to crush stones and non-soil debris greater than 2 mm in diameter. A 2-mm (#10-mesh) sieve is used to remove this debris. No further grinding or sieving should be required for field lab analyses. In our laboratory, samples are air-dried for a couple of days on clean sheets of office paper. Samples are either crushed and sieved at this time or returned to the original bag to await further processing.

Field laboratory measurements

In all tests for soil P, care must be taken to avoid contamination by hands, rubber stoppers, or detergents that might contain phosphate. Phosphate-free detergent is used to clean all glass and plasticware. In some cases, it may be necessary to rinse laboratory ware with 1 M HCl to eliminate P contamination.

Spot tests

The spot test for field P analysis was described by Eidt (1973). Briefly, the procedure calls for about 50 mg of fresh or prepared soil to be placed in the center of a filter-paper disk. Two drops of reagent A are added without touching the soil with the dropper tip (Eidt, 1973). After 30 s, two drops of reagent B are added. A blue color may appear after 2 min, and readings should be taken before 8 min pass. Visual ratings of the lengths and intensities of blue lines and rings are judged to give P ratings of none, weak, regular, good, or strong. The phosphorus spot test is simple and inexpensive, but the results are not quantitative. Values are affected by sample size, color perception of the analyst, and temperature, as well as other environmental conditions in the field or the laboratory. In addition, the dynamic range of P concentrations determined by the spot test is limited (Terry et al., 2000).

Mehlich III extractable phosphate procedure

Rypkema et al. (2007) adapted a Mehlich III (solution of acetic acid, ammonium nitrate, nitric acid, and ammonium fluoride) extraction method, for infield P prospection. They used a 5-min extraction time and employed syringe filtration with a glass fiber filter. They describe a two-part color development process that mixes 3 ml of extractant with 0.3 ml of a solution of ammonium molybdate and sulfuric acid and 0.3 ml of a solution of malachite green and polyvinyl acid. They reported that both reagent solutions were stable over time and temperature ranges, making them robust field materials. The extractant-reagent mixture develops color from a light yellow-green to a dark green with increasing P levels. Concentrations of P are determined by a battery-operated colorimeter at a wavelength of 620 nm.

Mehlich II extractable phosphate procedure

Terry et al. (2000) adapted a Mehlich II extraction procedure (Mehlich, 1978) for use in a field laboratory for P prospection at the ancient Maya site of Piedras Negras. Ready-mixed Hach reagents (Loveland, CO) were convenient for field laboratory extraction and molybdate-phosphate color development. Phosphorus concentrations were determined with the use of a battery-operated colorimeter. A field laboratory setup is shown in Figure 2.

The following method was used: Two grams of air-dried, sieved (<2-mm) soil sample were placed in one of six 50-ml glass vials attached to a board that facilitated shaking and processing of multiple samples. Once each soil sample was extracted with 20 ml of diluted Mehlich II solution for 5 min, the extractant was filtered and the filtrate collected in clean 50-ml vials. One milliliter of the extract was dispensed to a reaction vial and diluted to 10 ml with deionized water, and the contents of the PhosVer 3 powder pack were added to the vial. The sample was shaken by hand for exactly 1 min, and allowed to stand an additional 4 min for color development. The concentration of P in the samples was determined on a Hach DR 850 colorimeter at a wavelength of 610 nm.

Precautions should be taken with P extraction and analysis in the field lab:

1. Both the P extraction and the phosphate-molybdate and reductant reactions are temperature dependent. We found that once the temperature of the laboratory and the extractant solution exceeded 35 °C, the blue molybdate color appeared even with no phosphate in solution. To resolve this problem in a hot climate region, one should perform the analysis only in an air-conditioned space or in the cool of the morning. In the jungles of Guatemala, we finished our analysis before about 11 AM, as, afterward, the temperatures rose above 35 °C.
2. Another source of error to be avoided is the auto-reaction of the PhosVer 3 crystals. If the crystals are allowed to settle to the bottom of the reaction vial and

Field Geochemistry, Figure 2 The field laboratory set up near Tikal, Guatemala, for Olsen bicarbonate extraction and analysis of soil P.

to remain in proximity to each other, they will auto-react. The blue color will develop even if P is absent from the solution. The way to avoid this potential problem is to dissolve the reagents immediately. The contents of the PhosVer 3 packet can be added to one sample at a time and shaken for 60 s.

The colorimeter reports the percent transmittance of specific wavelengths of light. These transmittance values are then converted to ppm in the reaction solution according to a standard curve. The Mehlich II concentrate solution that is available from Hach Co. contains hazardous acids and thus is prohibited from transport within airline baggage. The reagent can be purchased in foreign countries from Hach distributers, but our experience has been that it takes about 1 year of difficult negotiations before the reagent is imported. As an alternative for use in calcareous soils and lime-stucco floors common to most ancient Maya sites, the Olsen bicarbonate (Olsen and Sommers, 1982) extraction can be successfully used in the place of the Mehlich II extraction.

Olsen bicarbonate extraction

The Olsen procedure was developed for determination of plant available P in neutral to alkaline soils that contain calcium carbonate. The P concentrations extracted by sodium bicarbonate from the soil tend to be lower than with the dilute acid Mehlich extractant, but the results in low P concentration samples compared to samples anthropogenically enriched in P are relative. The advantage of the bicarbonate extraction is that the reagent can be purchased at local markets and pharmacies. The concentration of sodium bicarbonate is 0.5 M and the extraction time with shaking is increased to 20 min. The samples are filtered and dispensed, and color is developed as indicated above. The PhosVer 3 reagents are acidic and will cause effervescence. It is a good idea to relieve pressure occasionally by cracking open the lid of the colorimeter vial and closing again for continued shaking.

Terry et al. (2000) subjected 35 soils of household middens, patios, and pathways from Piedras Negras, Guatemala, to the Eidt spot test, the Mehlich II extraction, the Olsen bicarbonate extraction, and the nitric/perchloric acid total P digestion procedures. While all four procedures identified high soil P levels in household middens and low P concentrations in patio and pathway soils, the Mehlich II dilute acid and the Olsen bicarbonate extraction procedures provided the greatest ratios of midden P concentrations to background P concentrations of 6.7 and 10.6, respectively (Table 1). The midden-background concentration ratios obtained by total digestion and the spot tests were 2.2 and 2.5, respectively.

Trace element analysis of soils

Elevated trace metal concentrations of Fe, Mn, and Cu could be indicative of mineral paints and pigments used in ancient times. Zinc is not a primary mineral pigment but may be present as a contaminant of mineral ores. A more likely source of Zn is the vegetable matter used in households. While Fe, Mn, and Cu are also trace constituents of foodstuffs, these minerals were also specifically collected and used in workshop activities.

Chelates are complex organic molecules that surround and hold in solution metallic ions that would otherwise quickly precipitate. The diethylenetriaminepentaacetic acid (DTPA) chelate extraction method (Lindsay and Norvell, 1978) can be used to solubilize surface adsorbed and slightly soluble trace metals that may be plant available. This method is often used in determining heavy

Field Geochemistry, Table 1 Summary comparison of soil P concentrations from 35 samples determined by four different extraction and total digestion procedures. The samples were obtained from groups O and N at Piedras Negras, Guatemala (Terry et al., 2000)

	Mehlich P mg/kg	Olsen P mg/kg	Total P mg/kg	Spot test Rating 1–5
Maximum	125	65	2,949	5
Minimum	17	5	1,042	2
Mean	33	19	1,854	4
STDEV	19	12	395	1
Background	19	6	1,132	2
Midden sample N6–7	125	65	2,476	5
Midden: background ratio	6.7	10.6	2.2	2.5

The "background" levels of P were determined by averaging 10 % of the samples lowest in concentration. The midden-background ratio was determined by dividing the P concentration of the soil at a known kitchen midden by the background concentration determined by each P analysis method

Spot test rating: 1 = no blue color development; 5 = a continuous ring of strong blue color development

metal contamination of environmental samples, and it is useful in characterizing the metal ions associated with human activities such as food use and mineral use in workshop activities. Unfortunately, the method does not lend itself well to the field laboratory, but if samples are returned to a formal laboratory possessing the necessary equipment, the procedure could be used. The concentrations of Cu, Fe, Mn, Pb, strontium (Sr), Zn, and other elements of interest can be determined simultaneously on the inductively coupled plasma atomic emission spectrometer (ICP-AES).

Portable X-ray fluorescence

The cutting-edge technology of portable X-ray fluorescence (pXRF) could be used to facilitate soil chemical analysis of total mineral elements in a field laboratory (Koester et al., 2003; Hou et al., 2004; Melquiades and Appoloni, 2004; Marwick, 2005; Jozic et al., 2009; Donais et al., 2010; Donais et al., 2011; Coronel et al. 2014). The pXRF instrument not only makes the work of elemental analysis possible in situ or in a field laboratory (Bernick et al., 1995; Radu and Diamond, 2009), but the analysis can be performed more economically and much faster than sending samples to an ICP laboratory facility for analysis. The pXRF is a battery-operated, handheld device that determines total elemental content for elements heavier than calcium. The instrument is about one-fifth of the cost of an ICP-AES and is fully functional in a field laboratory. The device is equipped with a probe window and an X-ray tube that irradiates the sample. The high-energy X-rays can either scatter or be absorbed by atoms in the sample and reradiated as X-rays of specific lower energy in a photoelectric effect. A rearrangement of electrons happens as a consequence of X-ray irradiation, which can cause ionization, or the ejection of an electron from an inner orbital. X-ray fluorescence is the emission of high-energy photons as an electron from a higher orbital replaces the one ejected, allowing the atom to return to normal energy levels. Using this method, concentrations of specific elements of interest can be measured by an X-ray fluorescence spectrometer contained in the device. The determined X-ray energy of the fluorescence is specific for each element (Bernick et al., 1995; Kalnicky and Singhvi, 2001; Jang, 2010), and the amount of radiation released is related to the concentration of an element in the sample (Juvonen et al., 2009).

Unfortunately, the pXRF analysis of soil P is not adequate to differentiate soils with subtle differences in anthropogenic P within activity areas. The energy emitted by P is low, and therefore, the error in P analysis by pXRF is large. In addition, the X-ray energy of P shows up on the shoulder of the energy peak for silicon (Si), so that the large Si content of soils increases the error in P concentration measurement (Coronel, 2011; Coronel et al., 2014). For this reason, it is recommended that one of the extractable P analyses be performed in the field lab. Several scientists are developing protocols for the use of pXRF in situ and in the field laboratory (e.g., Bernick et al., 1995; Kalnicky and Singhvi, 2001; Carr et al., 2008; Jang 2010; Martín Peinado et al., 2010; Coronel, 2011; Zhu et al., 2011; Davis et al., 2012; Weindorf et al., 2012a; Weindorf et al., 2012b; Coronel et al., 2014).

For pXRF analysis under ideal laboratory conditions, it is recommended that dry soil samples be ground to pass a -100-mesh (<0.149-mm) sieve and that the sample be contained behind 0.0036-mm plastic film (USEPA, 2007; Jang, 2010). In the field lab, it is more feasible to air-dry, crush, and sieve soils to 10 mesh (<2 mm) than to spend the time and labor to grind the samples to 100 mesh. Coronel and colleagues (2014) found no significant difference in the pXRF analyses of Ti, Fe, Cu, and Zn in samples crushed to pass either 10-mesh or 100-mesh sieves. Concentrations of Sr and Zr were attenuated by approximately 10 % when samples passed only a 10-mesh sieve. Prepared samples can be poured onto a 0.0036-mm film atop the pXRF window to a depth of 1–2 cm for an analysis time of 120 s. Compared to oven-dry samples, the X-ray signals from air-dry soil (about 96 % solids) were reduced by approximately 8 %, while elemental concentrations in field-moist soils (about 82 % solids) at approximately −33-kPa (−0.33-bar) moisture potential were attenuated by 11 %.

Further improvements of in situ protocols are needed, and more robust and less cumbersome pXRF instruments should be developed. Soil moisture and soil heterogeneity of in situ samples increase the error rate of pXRF measurements, but these error rates do not preclude the use of pXRF for qualitative and semiquantitative comparisons. In situ measurements could prove useful in initial screening of samples or in prospection for archaeological features. Deposition of workshop minerals, stucco floor materials, and the leveling of land surfaces by ancient people often change the elemental content of surface soils and of deposition horizons sufficiently that in situ measurements could prove useful. Sample preparation and pXRF measurement in the field laboratory produce reliable data for activity area analysis of ancient human activities.

Summary

The high surface area and chemical properties of soil particles allow the soil medium to preserve a geochemical record of human activities from ancient times to the present. The carbon and nitrogen components of perishable food and other household and workshop items decompose and are lost as gaseous and soluble substances, but P and certain trace nutrients, including Fe, Cu, Mn, and Zn, are adsorbed onto soil particles or precipitated as insoluble compounds and can remain for centuries. These geochemical residues serve as invisible artifacts. Soil geochemical methods are used in archaeology to locate ancient sites based on geochemical concentrations and help in the interpretation of ancient human activities. Spot tests, chemical extraction, and sample digestion procedures have been used to determine areas enriched in phosphate by ancient activities.

Protocols for portable X-ray fluorescence (pXRF) use in the field are being developed to facilitate soil chemical analysis of total mineral elements. In situ pXRF measurements could prove useful in initial screening of samples and in prospection for archaeological features. Unfortunately, the low-energy X-ray fluorescence from P and the interference of X-rays from soil Si render high-error and low-quality data for total soil P concentrations. However, chemical extraction procedures and battery-operated balances and colorimeters facilitate the collection of useful, high-quality P data from archaeological soils and floors in the field laboratory. The combination of appropriate sample preparation, chemical extraction of soil P, and pXRF measurement of metallic elements in the field laboratory produces reliable data for activity area analysis of ancient human behavior.

Bibliography

Abrahams, P. W., Entwistle, J. A., and Dodgshon, R. A., 2010. The Ben Lawers Historic Landscape Project: simultaneous multi-element analysis of former settlement and arable soils by x-ray fluorescence spectrometry. *Journal of Archaeological Method and Theory*, **17**(3), 231–248.

Arrhenius, O., 1931. Die Bodenanalyse im Dienst der Archäologie. *Zeitschrift fur Pflanzenernahrung Dungung Bodenkunde*, **10** (27–29), 427–439.

Bailey, G., 2007. Time perspectives, palimpsests and the archaeology of time. *Journal of Anthropological Archaeology*, **26**(2), 198–223.

Barba, L., 2007. Chemical residues in lime-plastered archaeological floors. *Geoarchaeology*, **22**(4), 439–452.

Barba, L., and Ortiz, A., 1992. Análisis químico de pisos de ocupación: un caso etnográfico en Tlaxcala, Mexico. *Latin American Antiquity*, **3**(1), 63–82.

Barba, L., Rodriguez Suárez, R., and Córdova, J. L., 1991. *Manual de técnicas microquímicas de campo para la arqueología*. Mexico: Universidad Nacional Autónoma de México, Instituto de Investigaciones Antropológicas.

Barba, L., de Pierrebourg, F., Trejo, C., Ortiz, A., and Link, K., 1995. Activités humaines reflétées dans les sols d'unités d'habitation contemporaine et préhispanique du Yucatan, Mexique: Études chimiques, ethnoarchéologiques et archéologiques. *Revue d'Archéométrie*, **19**, 79–95.

Barba, L. A., Ortiz, A., Link, K. F., López Luján, L., and Lazos, L., 1996. Chemical analysis of residues in floors and the reconstruction of ritual activities at the Templo Mayor, Mexico. In Orna, M. V. (ed.), *Archaeological Chemistry: Organic, Inorganic, and Biochemical Analysis*. Washington, DC: American Chemical Society. American Chemical Society Symposium Series, Vol. 625, pp. 139–156.

Bernick, M. B., Kalnicky, D. J., Prince, G., and Singhvi, R., 1995. Results of field-portable X-ray fluorescence analysis of metal contaminants in soil and sediment. *Journal of Hazardous Materials*, **43**(1–2), 101–110.

Bintliff, J. L., Gaffney, C., Waters, A., Davis, B., and Snodgrass, A., 1990. Trace metal accumulation in soils on and around ancient settlements in Greece. In Bottema, S. G., Entjes-Nieborg, G., and van Zeist, W. (eds.), *Man's Role in the Shaping of the Eastern Mediterranean Landscape*. Rotterdam: Balkema, pp. 159–172.

Carr, R., Zhang, C., Moles, N., and Harder, M., 2008. Identification and mapping of heavy metal pollution in soils of a sports ground in Galway City, Ireland, using a portable XRF analyser and GIS. *Environmental Geochemistry and Health*, **30**(1), 45–52.

Cavanagh, W. G., Hirst, S., and Litton, C. D., 1988. Soil phosphate, site boundaries, and change point analysis. *Journal of Field Archaeology*, **15**(1), 67–83.

Cook, D. E., Kovacevich, B., Beach, T., and Bishop, R. L., 2006. Deciphering the inorganic chemical record of ancient human activity using ICP-MS: a reconnaissance study of late Classic soil floors at Cancuén, Guatemala. *Journal of Archaeological Science*, **33**(5), 628–640.

Coronel, E. G., 2011. *Geochemical Analysis of Ancient Activities at Two Plazas in Cobá, Mexico*. MS thesis, Department of Plant and Wildlife Sciences, Brigham Young University, Provo.

Coronel, E. G., Bair, D. A., Brown, C. T., and Terry, R. E., 2014. The utility and limitations of portable X-ray fluorescence and field laboratory conditions on the geochemical analysis of soils and floors at areas of known human activities. *Soil Science*, **179**(5), 258–271.

Dahlin, B. H., Jensen, C. T., Terry, R. E., Wright, D. R., and Beach, T., 2007. In search of an ancient Maya market. *Latin American Antiquity*, **18**(4), 363–384.

Davis, L. G., Macfarlan, S. J., and Henrickson, C. N., 2012. A - PXRF-based chemostratigraphy and provenience system for the Cooper's Ferry site, Idaho. *Journal of Archaeological Science*, **39**(3), 663–671.

de Pierrebourg, F., 1999. *L'espace domestique Maya: Une approche ethnoarchéologique au Yucatan, Mexique*. Oxford: Archaeopress. Paris Monographs in American Archaeology 3. British Archaeological Reports, International Series, Vol. 764.

Donais, M. K., Duncan, B., George, D., and Bizzarri, C., 2010. Comparisons of ancient mortars and hydraulic cements through *in situ* analyses by portable X-ray fluorescence spectrometry. *X-Ray Spectrometry*, **39**(2), 146–153.

Donais, M. K., George, D., Duncan, B., Wojtas, S. M., and Daigle, A. M., 2011. Evaluation of data processing and analysis approaches for fresco pigment studies by portable X-ray fluorescence spectrometry and portable Raman spectroscopy. *Analytical Methods*, **3**(5), 1061–1071.

Dore, C. D., and López Varela, S. L., 2010. Kaleidoscopes, palimpsests, and clay: realities and complexities in human activities and soil chemical/residue analysis. *Journal of Archaeological Method and Theory*, **17**(3), 279–302.

Eidt, R. C., 1973. A rapid chemical field test for archaeological site surveying. *American Antiquity*, **38**(2), 206–210.

Entwistle, J. A., and Abrahams, P. W., 1997. Multi-element analysis of soils and sediments from Scottish historical sites. The potential of inductively coupled plasma-mass spectrometry for rapid site investigation. *Journal of Archaeological Science*, **24**(5), 407–416.

Entwistle, J. A., Abrahams, P. W., and Dodgshon, R. A., 1998. Multi-element analysis of soils from Scottish historical sites. Interpreting land-use history through the physical and geochemical analysis of soil. *Journal of Archaeological Science*, **25**(1), 53–68.

Entwistle, J. A., Abrahams, P. W., and Dodgshon, R. A., 2000. The geoarchaeological significance and spatial variability of a range of physical and chemical soil properties from a former habitation site, Isle of Skye. *Journal of Archaeological Science*, **27**(4), 287–303.

Fernández, F. G., Terry, R. E., Inomata, T., and Eberl, M., 2002. An ethnoarchaeological study of chemical residues in the floors and soils of Q'eqchi' Maya houses at Las Pozas, Guatemala. *Geoarchaeology*, **17**(6), 487–519.

Goffer, Z., 1980. Color: pigments and dyes. In *Archaeological Chemistry: A Sourcebook on the Applications of Chemistry to Archaeology*. New York: Wiley, pp. 167–196.

Holliday, V. T., and Gartner, W. G., 2007. Methods of soil P analysis in archaeology. *Journal of Archaeological Science*, **34**(2), 301–333.

Hou, X.-D., He, Y.-H., and Jones, B. T., 2004. Recent advances in portable X-ray fluorescence spectrometry. *Applied Spectroscopy Reviews*, **39**(1), 1–25.

Jang, M., 2010. Application of portable X-ray fluorescence (pXRF) for heavy metal analysis of soils in crop fields near abandoned mine sites. *Environmental Geochemistry and Health*, **32**(3), 207–216.

Jozic, M., Peer, T., and Malissa, H., 2009. Rapid test methods for the field screening of heavy metals in soil samples. *Water, Air, and Soil Pollution*, **199**(1–4), 291–300.

Juvonen, R., Parviainen, A., and Loukola-Ruskeeniemi, K., 2009. Evaluation of a total reflection X-ray fluorescence spectrometer in the determination of arsenic and trace metals in environmental samples. *Geochemistry: Exploration, Environment, Analysis*, **9**(2), 173–178.

Kalnicky, D. J., and Singhvi, R., 2001. Field portable XRF analysis of environmental samples. *Journal of Hazardous Materials*, **83** (1–2), 93–122.

Koester, C. J., Simonich, S. L., and Esser, B. K., 2003. Environmental analysis. *Analytical Chemistry*, **75**(12), 2813–2829.

Lindsay, W. L., 1979. *Chemical Equilibria in Soils*. New York: Wiley.

Lindsay, W. L., and Norvell, W. A., 1978. Development of a DTPA test for zinc, iron, manganese, and copper. *Soil Science Society of America Journal*, **42**(3), 421–428.

López Varela, S. L., and Dore, C. D., 2010. Social spaces of daily life: a reflexive approach to the analysis of chemical residues by multivariate spatial analysis. *Journal of Archaeological Method and Theory*, **17**(3), 249–278.

Lorch, W., 1940. Die siedlungsgeographische Phosphatmethode. *Die Naturwissenschaften*, **28**(40–41), 633–640.

Martín Peinado, F., Morales Ruano, S., Bagur González, M. G., and Estepa Molina, C., 2010. A rapid field procedure for screening trace elements in polluted soil using portable X-ray fluorescence (PXRF). *Geoderma*, **159**(1–2), 76–82.

Marwick, B., 2005. Element concentrations and magnetic susceptibility of anthrosols: indicators of prehistoric human occupation in the inland Pilbara, western Australia. *Journal of Archaeological Science*, **32**(9), 1357–1368.

Mehlich, A., 1978. New extractant for soil test evaluation of phosphorus, potassium, magnesium, calcium, sodium, manganese and zinc. *Communications in Soil Science and Plant Analysis*, **9**(6), 477–492.

Melquiades, F. L., and Appoloni, C. R., 2004. Application of XRF and field portable XRF for environmental analysis. *Journal of Radioanalytical and Nuclear Chemistry*, **262**(2), 533–541.

Middleton, W. D., and Price, D. T., 1996. Identification of activity areas by multi-element characterization of sediments from modern and archaeological house floors using inductively coupled plasma-atomic emission spectroscopy. *Journal of Archaeological Science*, **23**(6), 673–687.

Olsen, S. R., and Sommers, L. E., 1982. Phosphorus. In Page, A. L. (ed.), *Methods of Soil Analysis. Part 2, Chemical and Microbiological Properties*, 2nd edn. Madison, WI: American Society of Agronomy-Soil Science Society of America. Agronomy Monograph No. 9, pp. 403–430.

Parnell, J. J., Terry, R. E., and Golden, C., 2001. Using in-field phosphate testing to rapidly identify middens at Piedras Negras, Guatemala. *Geoarchaeology*, **16**(8), 855–873.

Parnell, J. J., Terry, R. E., and Nelson, Z., 2002. Soil chemical analysis applied as an interpretive tool for ancient human activities at Piedras Negras, Guatemala. *Journal of Archaeological Science*, **29**(4), 379–404.

Radu, T., and Diamond, D., 2009. Comparison of soil pollution concentrations determined using AAS and portable XRF techniques. *Journal of Hazardous Materials*, **171**(1–3), 1168–1171.

Rypkema, H. A., Lee, W. E., Galaty, M. L., and Haws, J., 2007. Rapid, in-stride soil phosphate measurement in archaeological survey: a new method tested in Loudoun county, Virginia. *Journal of Archaeological Science*, **34**(11), 1859–1867.

Terry, R. E., Nelson, S. D., Carr, J., Parnell, J., Hardin, P. J., Jackson, M. W., and Houston, S. D., 2000. Quantitative phosphorus measurement: a field test procedure for archaeological site analysis at Piedras Negras, Guatemala. *Geoarchaeology*, **15**(2), 151–166.

Terry, R. E., Fernández, F. G., Parnell, J. J., and Inomata, T., 2004. The story in the floors: chemical signatures of ancient and modern Maya activities at Aguateca, Guatemala. *Journal of Archaeological Science*, **31**(9), 1237–1250.

USEPA, 2007. *Method 6200: Field Portable X-ray Fluorescence Spectrometry for the Determination of Elemental Concentrations in Soil and Sediment*. Washington, DC: USEPA.

Vázquez Negrete, J., and Velázquez, R., 1996a. Análisis químico de materiales encontrados en excavación, dos casos: porta-incensarios tipo Palenque y cinabrio usado en practicas funerarias. In Macri, M. J., and McHargue, J. (eds.), *Eighth Palenque Roundtable, 1993*. San Francisco: The Pre-Columbian Art Research Institute, pp. 103–106.

Vázquez Negrete, J., and Velázquez, R., 1996b. Caracterización de materiales constitutivos de relieves en estucos, morteros y pintura mural de la zona arqueológica de Palenque, Chiapas. In Macri, M. J., and McHargue, J. (eds.), *Eighth Palenque Roundtable, 1993*. San Francisco: The Pre-Columbian Art Research Institute, pp. 107–112.

Walkington, H., 2010. Soil science applications in archaeological contexts: a review of key challenges. *Earth-Science Reviews*, **103**(3–4), 122–134.

Weindorf, D. C., Zhu, Y., Chakraborty, S., Bakr, N., and Huang, B., 2012a. Use of portable X-ray fluorescence spectrometry for environmental quality assessment of peri-urban agriculture. *Environmental Monitoring and Assessment*, **184**(1), 217–227.

Weindorf, D. C., Zhu, Y., Haggard, B., Lofton, J., Chakraborty, S., Bakr, N., Zhang, W., Weindorf, W. C., and Legoria, M., 2012b. Enhanced pedon horizonation using portable x-ray fluorescence spectrometry. *Soil Science Society of America Journal*, **76**(2), 522–531.

Wells, E. C., Terry, R. E., Parnell, J. J., Hardin, P. J., Jackson, M. W., and Houston, S. D., 2000. Chemical analyses of ancient anthrosols in residential areas at Piedras Negras, Guatemala. *Journal of Archaeological Science*, **27**(6), 449–462.

Wilson, C. A., Davidson, D. A., and Cresser, M. S., 2005. An evaluation of multielement analysis of historic soil contamination to differentiate space use and former function in and around abandoned farms. *Holocene*, **15**(7), 1094–1099.

Wilson, C. A., Cresser, M. S., and Davidson, D. A., 2006. Sequential element extraction of soils from abandoned farms: an investigation of the partitioning of anthropogenic element inputs from historic land use. *Journal of Environmental Monitoring*, **8**(4), 439–444.

Zhu, Y., Weindorf, D. C., and Zhang, W., 2011. Characterizing soils using a portable X-ray fluorescence spectrometer: 1. Soil texture. *Geoderma*, **167–168**, 167–177.

FIELD SURVEY

John Bintliff
School of Archaeology, Classics and History, Edinburgh University, Edinburgh, UK

Definition and introduction

Archaeological field survey refers to the systematic study of the surface traces of past human activity in the landscape (see also entry Landscape archaeology). The most common forms of such evidence are broken pottery and stone tools, but in protohistoric and historic societies, visible remains range from fragments of art through house foundations to standing monuments such as hillforts and temples.

Field survey

During the fifteenth to nineteenth centuries, landscape mapping of the more substantial forms of surface remains was the dominant aspect of archaeology, with excavation being much rarer and less sophisticated. Even after the development of scientific forms of excavation by the early twentieth century, wider research in the total landscape has remained of equal importance for compiling maps of past human activity in the countryside. This is due to the early recognition that the density of archaeological sites is far greater than the capacity of archaeologists to excavate them, especially in areas where human society has a long record of intensive settlement – such as Mesoamerica, the American Southwest, large parts of the Mediterranean and Near East, and Japan. Early collaboration with geographers, especially in the first half of the twentieth century, led to a lasting interest in settlement patterns, their evolution over time, and their relationship to the physical characteristics of a region. This also required a spatially wider investigation of human activity foci than targeted excavation or chance discoveries could provide (e.g., Fox, 1923).

The methodology of field survey has continuously improved in complexity over time, and practitioners are still in the process of evolving a rigorous and agreed-upon set of practices. It is typical even today for field survey projects to continue experimenting each year and for considerable diversity in approaches to occur among projects. Initially, "topographers" travelled extensively into the countryside, often with ancient texts in hand when historic sites were mentioned or with advice from local villagers as to where "remains" of all kinds were known. Recording began with ruins and earthworks in the early centuries, supplemented by coins and sculpture, but by the late nineteenth century, the importance of the everyday, and far more plentiful, human traces such as potsherds and stone tools was realized, as such finds allowed a far greater range of sites to be discovered while providing the primary means – still true today – of dating the periods of time in the past during which a given findspot was in use.

This new phase of survey history, with its focus on pottery and lithics backed up by the evidence of ruined structures where preserved, was practiced with what today would be called "grab samples": small collections of hopefully diagnostic artifacts that would provide chronological information and some idea of site function for a findspot (e.g., settlement, burial, temporary activity in the landscape such as a hunting stand, or seasonal farming base). Moreover, the coverage of a region was still "extensive," and surveyors ranged over large areas in vehicles or on foot, gaining a general impression of the kinds of site to be encountered and the overall balance of activities from phase to phase. By the 1950s, major programs of regional survey were set in motion in different parts of the world, each conceived with a conscious intention to tackle specific historical problems. What set these projects apart from most earlier endeavors was their large scale, the deliberate inclusion of a range of complementary disciplines in addition to archaeology, and the "problem orientation" planned within a regional framework. Among the most noteworthy, during which chosen sites were also excavated on occasion, were (1) the team led by Robert Braidwood (Braidwood, 1937; Braidwood et al., 1983) researching the origins of agriculture in the Fertile Crescent of the Near East, followed by (2) Robert McCormick Adams's (1965, 1981) studies of the long-term settlement development of later prehistoric to historic Southern Mesopotamia, (3) the Valley of Tehuacán project of Richard MacNeish (1967–1972) (also particularly focused on the development from hunter-gatherers through the earliest maize farmers to the rise of civilization), (4) the South Etruria Survey led by John Ward-Perkins (Potter, 1979), and (5) the Messenia Project directed by William McDonald and Richard Hope Simpson (McDonald and Rapp, 1972) (see entry Minnesota Messenia Expedition (MME)). As these pioneering major projects proceeded, experiments were conducted with more systematic site-mapping and artifact collection procedures commensurate with the quantitative emphasis of the "New Archaeology," which in the 1960s–1970s urged that survey be brought within the model of experimental science (e.g., Redman and Watson, 1970; Flannery, 1976).

During the 1980s and 1990s, a new generation of regional projects adopted a more complete, "intensive" survey procedure, where each field or artificial study block (sometimes called a transect) in the landscape was walked at close intervals (5–20 m usually between fieldwalkers) so that even small artifact concentrations would be encountered (what this writer dubbed in 1994 the "New Wave" surveys). Visibility measurements were taken in order to control for differential recognition of sites due to the variable density of surface vegetation, and geomorphologists were increasingly deployed on the team to identify areas of likely loss or burial of artifacts due to erosion or colluvial-alluvial processes (e.g., Cherry et al., 1988). In the latter part of this phase, the concept of "non-site" survey emerged in the United States and was more generally adopted; it recognized that the landscape between the activity concentrations termed "sites" often contained significant numbers of dispersed artifacts. It became common to refocus surface survey onto the mapping of individual artifacts across the landscape, with a secondary stage being the identification of the patterns in these total distributions and the variable processes that might have created them. Besides the effects of weather, cultivation, or construction activities, which could shift artifacts out of sites into their immediate surroundings, more distant scatters could be shown to reflect "taskscapes" in the countryside: temporary bases for hunting or farming, mining, etc. An additional category was given prominence by the Near Eastern regional surveys of Wilkinson, where intensive agricultural manuring in certain periods of the past, using undifferentiated domestic rubbish, had resulted in extensive carpets of artifacts across the landscape radiating from settlement sites (Bintliff and Snodgrass, 1988a; Wilkinson, 1989). Although criticized by some, subsequent exhaustive investigations leave little doubt that in some landscapes and usually for restricted periods, massive manuring did indeed occur, with major implications, as Wilkinson argued, for detecting population pressure and ecological sustainability (e.g., Bintliff et al., 2007). Finally, motivated by the pioneer survey of the New World's largest pre-Columbian agglomeration, Teotihuacan (Millon, 1964), it proved possible to survey large urban sites in a relatively short period of one or several seasons (e.g., Bintliff and Snodgrass, 1988b; Bintliff, 2014).

As the shift from a non-site approach to regional survey occurred, awareness was growing that even if conducted on a field-by-field basis, intensive surveys detected only a certain sample of past activity in the landscape. The problem lay in evaluating what was missed and whether there were ways to compensate for such omissions. One filter was already noted: the geomorphological constraints that determined whether surface artifacts and sites could be seen at the present day (van Leusen et al., 2011). Advice from project geoarchaeologists could sensitize surveys to those localities unlikely to provide "windows" into past landscapes, and these might be omitted from study or alternatively (but rarely) probed by coring if remains were expected to be buried. Vegetation cover – grassland or forest – posed seemingly equal hindrances to effective surface survey, but coping methods have included focusing on areas temporarily opened by fire as well as shovel-pit testing, in which numerous small units one or a few meters square are stripped to the subsoil to evaluate buried finds (reviewed by Shott, 1985). On a more archaeological front, the relative survival and visibility of artifacts themselves have been raised as limiting factors in site recognition, i.e., the "hidden landscape" concept (Bintliff et al., 1999), which implies that for some eras of the past, even a handful of surface finds may represent a significant former activity focus.

In the heyday of "New Archaeology" in the 1960s–1970s, it appeared attractive to limit overall landscape coverage, the area of a located site to be studied, or the amount of artifacts to be collected, through an explicit sampling strategy linked to statistical methodologies, such as stratified sampling in which homogeneous subareas (strata) would be identified and sampled independently (cf. Cherry et al., 1978; Renfrew and Wagstaff, 1982). Warnings about such procedures (already in Flannery, 1976) have not prevented their continued use, the central failing being the concept of designing a reliable sample of a larger whole whose properties are unknown. More experiments are required where samples are compared with complete spatial coverage and artifact samples with total surface collection, before such shortcuts can be recommended.

Since the late 1990s and early 2000s, a wider process of rethinking the methodology and interpretative potential of surface surveys has been in operation as a form of "source criticism." Comparative survey analysis, where practitioners review each other's methods, theories, and interpretations and attempt to amalgamate data from separate surveys, is one aspect of this reevaluation (cf. Bintliff et al., 2000; Alcock and Cherry, 2004). Two practical examples are Farinetti's integration of site data from all forms of surface research since the nineteenth century for the central Greek province of Boeotia (Farinetti, 2011) and Gkiasta's overview of the history and results of survey on the island of Crete (Gkiasta, 2008). Another aspect of rethinking survey approaches is the publication of surface survey manuals (e.g., Banning, 2002).

Finally, one can mention a number of extra dimensions to traditional survey which are being increasingly featured in published projects. Some surveys have deliberately worked in terrain not considered ideal for surface survey, such as mountain zones, tropical forests, pastoral lowlands, or dune environments, where a range of additional techniques have been necessary to deal with problems of site detection. Problem periods, or past intervals for which it has proved difficult to find significant numbers of activity foci, have led to predictive modeling based on compiled evidence that isolates landscape characteristics where survey is more likely to recover adequate data (e.g., Paleolithic-Mesolithic sites in semiarid environments, Runnels et al., 2005). Scientific aids have become more frequently used as additional means to study past settlements, such as a battery of geophysical methods to map subsurface features, geochemical soil testing to detect human activity zones, aerial photography, and satellite imaging (e.g., Philip et al., 2005) (see entries Remote Sensing in Archaeology; Geophysics; Electrical Resistivity and Electromagnetism). Geographical information systems (GIS) have brought two contrasting advantages to field survey. First, GIS using palmtops and GPS links can allow accurate and speedy plotting of landscape units under study in the field as well as recording data in real time, and second, GIS can assist the recent interest in the phenomenology of landscape through estimating human navigation potential and the sensory perception of a particular terrain. There remains, however, a considerable lack of experimental evidence on the effects of using different methodologies on the data produced through survey, and many key issues are still uncertain. These issues include (1) the desired size and composition of artifact samples to achieve reliable representativeness for an activity focus (Bintliff, 2012), (2) the best way to reconstruct demographic estimates from survey data, and (3) whether regional surface survey can move from generalized pictures of the long and medium term (thousands to hundreds of years) to detect the dynamism of human settlement at the historical scale of decades or even individual years.

Bibliography

Adams, R. M. C., 1965. *The Land Behind Baghdad: A History of Settlement on the Diyala Plains*. Chicago: University of Chicago Press.

Adams, R. M. C., 1981. *Heartland of Cities: Surveys of Ancient Settlements and Land Use on the Central Floodplain of the Euphrates*. Chicago: University of Chicago Press.

Alcock, S. E., and Cherry, J. F. (eds.), 2004. *Side-by-Side Survey. Comparative Regional Studies in the Mediterranean World*. Oxford: Oxbow.

Banning, E. B., 2002. *Archaeological Survey*. New York: Kluwer Academic/Plenum Press.

Bintliff, J. L., 2012. Contemporary issues in surveying complex urban sites in the Mediterranean region: the example of the city of Thespiai (Boeotia, Central Greece). In Vermeulen, F., Keay, S. J., Burgers, G.-J., and Corsi, C. (eds.), *Urban Landscape Survey in Italy and the Mediterranean*. Oxford: Oxbow, pp. 44–52.

Bintliff, J. L., 2014. Intra-site artefact surveys. In Corsi, C., Slapšak, B., and Vermeulen, F. (eds.), *Good Practice in Archaeological Diagnostics: Non-invasive Survey of Complex Archaeological Sites*. Cham: Springer, pp. 193–207.

Bintliff, J. L., and Snodgrass, A. M., 1988a. Off-site pottery distributions: a regional and interregional perspective. *Current Anthropology*, **29**(3), 506–513.

Bintliff, J. L., and Snodgrass, A. M., 1988b. Mediterranean survey and the city. *Antiquity*, **62**(234), 57–71.

Bintliff, J. L., Howard, P., and Snodgrass, A. M., 1999. The hidden landscape of prehistoric Greece. *Journal of Mediterranean Archaeology*, **12**(2), 139–168.

Bintliff, J. L., Kuna, M., and Venclová, N. (eds.), 2000. *The Future of Surface Artefact Survey in Europe*. Sheffield: Sheffield Academic Press.

Bintliff, J. L., Howard, P., and Snodgrass, A. M. (eds.), 2007. *Testing the Hinterland: The Work of the Boeotia Survey (1989–1991) in the Southern Approaches to the City of Thespiai*. Cambridge: McDonald Institute Monographs, University of Cambridge.

Braidwood, R. J., 1937. *Mounds in the Plain of Antioch. An Archaeological Survey*. Chicago: University of Chicago Press. Oriental Institute Publications, Vol. 48.

Braidwood, L. S., Braidwood, R. J., Howe, B., Reed, C., and Watson, P. J. (eds.), 1983. *Prehistoric Archeology Along the Zagros Flanks*. Chicago: University of Chicago Press. Oriental Institute Publications, Vol. 105.

Cherry, J. F., Gamble, C., and Shennan, S. J. (eds.), 1978. *Sampling in Contemporary British Archaeology*. British Archaeological Reports, British Series 50. Oxford: British Archaeological Reports.

Cherry, J. F., Davis, J. L., Demitrack, A., Mantzourani, E., Strasser, T. F., and Talalay, L. E., 1988. Archaeological survey in an artifact-rich landscape: a Middle Neolithic example from Nemea, Greece. *American Journal of Archaeology*, **92**(2), 159–176.

Farinetti, E., 2011. *Boeotian Landscapes: A GIS-based Study for the Reconstruction and Interpretation of the Archaeological Datasets of Ancient Boeotia*. Oxford: Archaeopress. British Archaeological Reports, International Series S2195.

Flannery, K. V. (ed.), 1976. *The Early Mesoamerican Village*. New York: Academic.

Fox, C., 1923. *The Archaeology of the Cambridge Region*. Cambridge: Cambridge University Press.

Gkiasta, M., 2008. *Historiography of Landscape Research on Crete*. Leiden: Leiden University Press. Archaeological Studies Leiden University, Vol. 16.

McDonald, W. A., and Rapp, G. R. (eds.), 1972. *The Minnesota Messenia Expedition: Reconstructing a Bronze Age Regional Environment*. Minneapolis: University of Minnesota.

McNeish, R. S. (ed.), 1967–1972. *The Prehistory of the Tehuacán Valley, vols. 1–5*. Austin: University of Texas.

Millon, R., 1964. The Teotihuacan Mapping Project. *American Antiquity*, **29**(3), 345–352.

Philip, G., Abdulkarim, M., Newson, P., Beck, A., Bridgland, D. R., Bshesh, M., Shaw, A., Westaway, R., and Wilkinson, K., 2005. Settlement and landscape development in the Homs region, Syria. Report on work undertaken during 2001–2003. *Levant*, 37: 21–41.

Potter, T. W., 1979. *The Changing Landscape of South Etruria*. London: Elek.

Redman, C. L., and Watson, P. J., 1970. Systematic, intensive surface collection. *American Antiquity*, **35**(3), 279–291.

Renfrew, C., and Wagstaff, J. M. (eds.), 1982. *An Island Polity. The Archaeology of Exploitation in Melos*. Cambridge: Cambridge University Press.

Runnels, C., Panagopoulou, E., Murray, P., Tsartsidou, G., Allen, S., Mullen, K., and Tourloukis, E., 2005. A Mesolithic landscape in Greece: testing a site-location model in the Argolid at Kandia. *Journal of Mediterranean Archaeology*, **18**(2), 259–285.

Shott, M., 1985. Shovel-test sampling as a site discovery technique: a case study from Michigan. *Journal of Field Archaeology*, **12**(4), 457–468.

Van Leusen, M., Pizziolo, G., and Sarti, L. (eds.), 2011. *Hidden Landscapes of Mediterranean Europe. Cultural and Methodological Biases in Pre- and Protohistoric Landscape Studies: Proceedings of the International Meeting, Siena, Italy, May 25–27, 2007*. British Archaeological Reports, International Series 2320. Oxford: Archaeopress.

Wilkinson, T. J., 1989. Extensive sherd scatters and land-use intensity: some recent results. *Journal of Field Archaeology*, **16**(1), 31–46.

Cross-references

Alluvial Settings
Colluvial Settings
Electrical Resistivity and Electromagnetism
Field Geochemistry
Geophysics
Geographical Information Systems (GIS)
Landscape Archaeology
Minnesota Messenia Expedition (MME)
Paleoenvironmental Reconstruction
Soils, Agricultural

FISSION TRACK DATING

Barry Kohn
School of Earth Sciences, University of Melbourne, Melbourne, VIC, Australia

Definition

Fission track dating is a radiometric method of age determination based on the accumulation within insulating solids of damage trails formed by the spontaneous nuclear fission decay of the uranium isotope ^{238}U.

Principles

The main mode of radioactive decay for the ^{238}U nucleus is α-particle emission; however, about one in every two million decays is by nuclear fission. During fission, the heavy, unstable nucleus splits into two uneven, positively charged fragments. The two fragments are propelled in opposite directions from the reaction site, dissipating their considerable excess kinetic energy in the host crystal lattice. This interaction disrupts the crystal structure creating a single linear damage trail at the atomic scale. The trails cannot be observed optically, but because they are very reactive, they can be enlarged with chemical etchants to become visible under an optical microscope. The maximum size of an etched fission track depends on the physical and chemical properties of the host mineral but is typically about 11–17 μm long and 1–2 μm wide. Although spontaneous fission occurs in other naturally occurring heavy isotopes (e.g., ^{235}U and ^{232}Th), their half-lives are too long to produce a significant number of tracks. The time span over which fission track dating can be applied is very broad and is essentially determined by the areal density of fission tracks preserved in the material of interest. Cultural objects only several decades in age to minerals and glasses, some over a billion years old, have been dated by this method.

Materials and analysis

Uranium is present as a trace element in many of the minor rock-forming minerals, e.g., apatite (calcium phosphate), zircon (zirconium silicate), and titanate (calcium titanium silicate), as well as volcanic glass. As for any radioactive decay process, spontaneous fission occurs with a specific decay rate constant, so that the measurement of the number of tracks and ^{238}U content – determined by either neutron irradiation in a nuclear reactor or by laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) – can be used to calculate a fission track age for a mineral grain or glass fragment. Precision of the dating depends mainly on the number of fission tracks counted in mineral grains, as well as in standard glass monitors (where ^{238}U content is determined by neutron irradiation) or from calculated analytical uncertainties (where ^{238}U content is measured by LA-ICP-MS).

Applications

Fission track ages can be applied in two ways.

First, where mineral samples have cooled rapidly and remained thermally “undisturbed” relatively close to or at the Earth’s surface, they may be used to determine absolute ages, e.g., volcanic units, meteorite impact events, and kimberlite emplacement.

Second, at elevated temperatures, tracks may be partially or entirely erased by thermal annealing (repair of track damage), during which they are gradually restored to the ordered structure of the crystalline matrix by progressive shrinkage from each end. For apatite, a commonly studied mineral, most track annealing proceeds progressively between about 60 and 110 °C (but this varies with heating time and chemical composition), with the fission track clock being reset to zero with total track erasure. The annealing temperature range is equivalent to depths between about 2 and 6 km in the uppermost part of the Earth’s crust. By analyzing fission track age and track length information, the thermal history of samples collected at the Earth’s surface or in deep boreholes can be determined. This provides unique information for reconstructing geological histories in terms of processes such as tectonism, fluid flow, and landscape evolution. Fission track thermal history studies have been applied to a wide range of geological problems, e.g., sedimentary basin evolution, sedimentary provenance, structural development of orogenic belts, and continental denudation patterns (e.g., Gallagher et al., 1998; Dumitru, 2000; Gleadow et al., 2002).

Archaeological applications have been related mostly to dating of man-made glasses, ceramics, obsidian, and heated stones (e.g., Wagner and van den Haute, 1992). Because of the long half-life of spontaneous uranium fission and the relative youthfulness of archaeological materials, this often requires large samples with relatively high uranium concentrations. Such circumstances are rare, which limits the archaeological application of fission track dating. Probably the best application to address archaeological questions is where the age of hominin or artifact-bearing strata can be constrained by their stratigraphic relation to datable volcanic units, particularly using zircon (e.g., Gleadow, 1980; Morwood et al., 1998). Fission track dating of unheated obsidian artifacts and their uranium content may be characteristic of a particular source area which, if matched, may provide information on ancient trade routes. Alternatively, if heat has been applied to an obsidian artifact resulting in track annealing, then study of the diameter of etched tracks can be used to determine whether the fission track clock was partially or totally reset, allowing the age of the artifact's manufacture or use to be constrained (e.g., Miller and Wagner, 1981).

Bibliography

Dumitru, T. A., 2000. Fission-track geochronology. In Noller, J. S., Sowers, J. M., and Lettis, W. R. (eds.), *Quaternary Geochronology: Methods and Applications*. Washington, DC: American Geophysical Union. American Geophysical Union Reference Shelf, Vol. 4, pp. 131–156.

Gallagher, K., Brown, R., and Johnson, C., 1998. Fission track analysis and its applications to geological problems. *Annual Review of Earth and Planetary Sciences*, **26**, 519–572.

Gleadow, A. J. W., 1980. Fission track age of the KBS Tuff and associated hominid remains in northern Kenya. *Nature*, **284**(5753), 225–230.

Gleadow, A. J. W., Belton, D. X., Kohn, B. P., and Brown, R. W., 2002. Fission track dating of phosphate minerals and the thermochronology of apatite. In Kohn, M. J., Rakovan, J., and Hughes, J. M. (eds.), *Phosphates – Geochemical, Geobiological and Material Importance*. Reviews in Mineralogy and Geochemistry, Vol. 48, pp. 579–630.

Miller, D. S., and Wagner, G. A., 1981. Fission-track ages applied to obsidian artifacts from South America using the plateau-annealing and the track-size age-correction techniques. *Nuclear Tracks*, **5**(1–2), 147–155.

Morwood, M. J., O'Sullivan, P. B., Aziz, F., and Raza, A., 1998. Fission-track ages of stone tools and fossils on the east Indonesian island of Flores. *Nature*, **392**(6672), 173–176.

Wagner, G. A., and van den Haute, P., 1992. *Fission-Track Dating*. Dordrecht: Kluwer.

Cross-references

$^{40}Ar/^{39}Ar$ and K–Ar Geochronology
Cosmogenic Isotopic Dating
Glass
Inductively Coupled Plasma-Mass Spectrometry (ICP-MS)
Optically Stimulated Luminescence (OSL) Dating
Paleomagnetism
Radiocarbon Dating
U-Series Dating
Volcanoes and People

FLUORINE DATING

Matthew R. Goodrum
Department of Science and Technology in Society, Virginia Tech, Blacksburg, VA, USA

Synonyms

Fluoride dating; Fluorine absorption dating

Definition

Fluorine dating is a method that measures the amount of fluoride absorbed by bones in order to determine their relative age. Unlike radiometric dating methods, it cannot provide a chronometric (or calendrical) date. Fluorine dating provides only a relative date for bone, revealing whether specimens are older or younger than one another or if they are of the same age (Berger and Protsch, 1991; Lyman et al., 2012).

Fluorine dating relies on the discovery that bone mineral, calcium hydroxyapatite, will absorb fluoride ions if, during burial, it is exposed to groundwater that contains fluoride. Groundwater and soil in most parts of the world contain small amounts of fluoride, and these ions can replace the hydroxyl ions in bone mineral to form fluorapatite. In this way, the chemically unstable $Ca_{10}(PO_4)_6(OH)_2$ is gradually replaced by the more stable $Ca_5(PO_4)_3F$. Bones absorb fluoride over time, and as a result, those that were buried long ago will contain more fluoride than those buried more recently. However, since fluoride concentrations vary significantly in different geographical areas because of sediment chemistry as well as sediment hydrology, this method is reliable only when bones from the same location are compared. Furthermore, bone density and size also affect fluorine absorption, so not all types of bone in a skeleton will absorb fluorine at the same rate. Thus, caution is required when employing this method, and for these reasons, as well as the development of other dating methods, fluorine dating fell out of common use over the last half century.

History

In the 1890s, the French paleontologist Emile Rivière solicited the assistance of Adolphe Carnot, a chemist at the School of Mines in Paris, to test human bones he had excavated along with Pleistocene animal fossils in caves near the town of Menton in southern France in order to determine if the human and animal bones were of the same age. Carnot developed techniques for measuring the fluorine content of fossil bones and conducted tests to demonstrate the validity of his new fluorine dating method. Carnot's method was successfully used in the 1890s to settle questions about the relative ages of contested human fossils found with Pleistocene animals, but the method soon fell into disuse. The English geologist Kenneth Oakley reintroduced the method in 1947 and later used it to resolve the contentions problem of the Piltdown Man fossils. Charles Dawson originally collected the skull fragments and partial jaw bone of Piltdown Man in southern England between 1908 and 1912. This presumed ancient hominin was greeted with great excitement in Britain, yet from the start there were doubts about the antiquity of the fossils and whether the jaw and skull bones belonged to the same creature. Oakley collaborated with chemist Randall Hoskins to test the Piltdown finds and eventually showed that the jaw was significantly younger than the skull bones and that both were younger than the

Pleistocene animal fossils found nearby. The fluorine dating method contributed to other evidence that convincingly demonstrated that the Piltdown fossils were a forgery. More importantly, Oakley used this method to settle disputes over other contested prehistoric human fossils (Goodrum and Olson, 2009).

Bibliography

Berger, R., and Protsch, R., 1991. Fluorine dating. In Göksu, H. Y., Oberhofer, M., and Regulla, D. (eds.), *Scientific Dating Methods*. Dordrecht: Kluwer, pp. 251–270.

Goodrum, M. R., and Olson, C., 2009. The quest for an absolute chronology in human prehistory: anthropologists, chemists and the fluorine dating method in palaeoanthropology. *British Journal for the History of Science*, **42**(1), 95–114.

Lyman, R. L., Rosania, C. N., and Boulanger, M. T., 2012. Comparison of fluoride and direct AMS radiocarbon dating of black bear bone from Lawson Cave, Missouri. *Journal of Field Archaeology*, **37**(3), 226–237.

Cross-references

$^{40}Ar/^{39}Ar$ and K–Ar Geochronology
Archaeomagnetic Dating
Dendrochronology
Fission Track Dating
Paleomagnetism
Radiocarbon Dating
U-Series Dating

FORENSIC GEOARCHAEOLOGY

J. M. Adovasio
Research Programs/Services, Florida Atlantic University–Harbor Branch, Fort Pierce, FL, USA

Definition

Forensic Geoarchaeology: The application of multidisciplinary, high-resolution analytical techniques from geology, archaeology, physical science, and earth science in the examination, recovery, and interpretation of outdoor crime scenes.

Introduction

Prior to the early 1980s, forensic geoarchaeology essentially did not exist. While the geological "context" of outdoor crime scenes had been scrutinized to varying degrees for more than a century, the use of high-resolution, geoarchaeological analytical protocols in forensic applications was unknown. The genesis of forensic geoarchaeology as a subdiscipline took place as a result of an unusual turn of events. A particular series of geoarchaeological evaluations of criminal evidence, narrowly circumscribed in time, illustrated their power in revealing information useful in a court of law.

In the late spring of 1984, the author was contacted by the then state archaeologist of Utah, D. Brigham Madsen, who inquired into the excavation protocols and attendant analyses conducted during the excavations at Meadowcroft Rockshelter, Washington County, Pennsylvania, in the 1970s. The protocols had been initiated and refined by James Adovasio, Jack Donahue, and Gary Cooke as tools in the investigation of the deeply stratified, multicomponent closed site located on an unglaciated portion of the Allegheny Plateau approximately 46 km southwest of Pittsburgh (Figure 1). From its first season in 1973 to the present, this locality has been the focal point of an intensive multidisciplinary, research project that has generated hundreds of publications and technical papers. Long famous, or infamous, for the controversial dating of its early occupational components, the site is equally well known, albeit in much smaller circles, for the extreme rigor and great precision of the excavation, analytical, and documentary methodologies employed. Unlike the age of the earliest deposits, these protocols were never the subject of any debate.

Of greatest interest to the Utah state archaeologist were the techniques used to excavate and characterize the many microstrata which composed most of the 11 major depositional units at the site (Figure 2). In some cases, these microstrata were thinner than a trowel blade ($\sim$1.35 mm) and were often tediously excavated with single-edged razor blades. Moreover, they represented, in depositional terms, just moments in time. By 1984, many of these microstrata had been subjected to a battery of macro- and micro-sedimentological analyses involving both conventional (i.e., sieve based) grain size study and rigorous instrumental compositional analyses. Among the latter were Coulter counter-based quantification of silt-sized materials (which represented the first use of this technique in North American closed site archaeology), a variety of geochemical assays, and even scanning electron microscopy (SEM) of individual sand grains. The original purpose of these analyses was to provide objective verification of the subjectively perceived differences between these microstrata in order to elucidate subtle changes in the depositional history of the site. Each microstratum had a distinctive suite of physical and geochemical attributes, i.e., each had a unique microsedimentary signature.

The Utah state archaeologist was interested to know whether the rigorous and detailed analyses conducted at Meadowcroft Rockshelter could be applied to legal cases in a forensic evidentiary capacity, and the results of several first "trials" represented the "birth" of forensic geoarchaeology.

Forensic applications

The main task in 1984 was to exploit the analytical techniques used to discriminate the Meadowcroft microstrata in the cause of helping to adjudicate ARPA violations. ARPA refers to the Archaeological

Forensic Geoarchaeology, Figure 1 General view of the new protective structure/visitors platform at Meadowcroft Rockshelter. The work here has directly led to the development of the forensic geoarchaeological techniques discussed in this entry.

Forensic Geoarchaeology, Figure 2 General view of some of the microstratigraphy at Meadowcroft Rockshelter.

Resources Protection Act of 1979, enacted to protect sites and other cultural remains on public and Indian lands from vandalism and theft. The "test case" that would become the template for all future applications was USA versus Earl K. Shumway, a notorious and, to some, a near mythic figure in the history of archaeological looting in the Greater American Southwest.

Horse Rock Ruin litigation

In April of 1984, E. K. Shumway of Blanding, Utah, plundered a cache of 28–32 Pueblo III coiled and plaited baskets from Horse Rock Ruin, in the Monticello Ranger District of the Manti-La Sal National Forest, San Juan County, Utah. Horse Rock Ruin lies within an area locally known as Jack's Pasture. The USDA Forest Service recovered about one half of the collection, which was used along with other evidence in the subsequent indictment of Shumway on 14 November 1984.

Shumway maintained that the baskets in question were ethnographic materials and did not derive from a site on federal property but rather from a site or sites on private land (which would not have been an ARPA violation). This claim has become the standard alibi in virtually all similar ARPA cases. The baskets were sent to the author for evaluation, and our collective cooperation was solicited in demonstrating that these items did, in fact, derive from Horse Rock Ruin (Donahue and Adovasio, 1986). The procedures are described in the following paragraphs.

Detailed attribute analysis of the basketry clearly demonstrated that, contrary to Shumway's claim, the items were all of Pueblo III Anasazi (or, in contemporary jargon, Ancestral Pueblo) ascription and, in fact, probably represented a single aboriginal caching event from the thirteenth century (Adovasio and Andrews, 1990).

In order to establish the provenience of the baskets, a wide range of sediment samples was obtained and analyzed. These samples included sediments from the Horse Rock Ruin itself, the roof and walls of the alcove immediately contiguous to the suspected location of illicit digging, and other nearby alcoves. Small samples were extracted from the recovered baskets, and additional surface samples taken from federal and private lands were also included for comparison.

Eighty-five sediment samples were analyzed in all, including 9 from the baskets, 58 from the Horse Rock Ruin site and contiguous alcove, 8 from four other alcoves, and 2 from open locations in the Jack's Pasture area. Interestingly, though Shumway had carefully cleaned the baskets, sufficient sediment remained under the stitches or between the plaiting elements to permit removal of enough material for analytical purposes. Indeed, the great advantage to some of these analytical techniques is that they require less sediment than normally accumulates under a gardener's fingernails.

All bulk samples were sieved through a 1 mm screen to remove coarse sand and pebbles, and the sifted fraction was then passed through a riffle sample splitter to obtain a representative subsample weighing less than 10 g. These samples were then crushed via mortar and pestle and transferred to sample cups covered with Mylar for analysis by energy dispersive X-ray fluorescence (XRF).

The X-ray fluorescence analysis detects elements heavier than aluminum and was performed on a Tracor Northern Spectrace 440 spectrometer. Two scans were made: one at 20 kV and 0.1 mA and the other at 35 kV and 0.1 mA with a thin molybdenum window to block out most of the direct signal from the molybdenum X-ray tube. The spectrum at each setting was recorded for 100 s. The individual spectral lines for the elements were identified, and their intensities were recorded. United States Geological Survey standards were also analyzed to provide calibration coefficients for the calculation of element concentrations from the intensity data. Selected samples were also analyzed by X-ray diffraction (XRD), a method which identifies the mineral phases in which the elements occur. The diffraction analysis was run on a General Electric XRD-5 unit with a copper X-ray tube at 35 kV and 15 mA. Medium resolution slits were used and a scanning rate of 2.2 was employed.

The XRF analysis detected the presence of the following elements: aluminum, silicon, sulfur, chlorine, potassium, calcium, titanium, manganese, iron, copper, zinc, bromine, arsenic, rubidium, strontium, and zirconium (Table 1). Copper, bromine, and arsenic were detected in only a few (less than ten) samples and seemed to show no specific trend in their occurrence. Aluminum was detected in about one third of the samples but is probably present in all of them; the detection capability of XRF for aluminum (and light elements such as magnesium, sodium, and carbon) is extremely poor, and because of this, no attempt was made to determine the actual amount of aluminum present in the samples. Zirconium concentrations were also not determined exactly. Imprecision in the analysis of the latter element results from the interface of the molybdenum X-ray tube peaks with the zirconium peaks.

Concentrations of elemental silicon, potassium, calcium, sulfur, chlorine, manganese, titanium, iron, zinc, strontium, and rubidium were also used to calculate their oxide content. The difference between the sum of these elements and oxides and 100 % represents the missing elements: carbon, sodium, magnesium, and aluminum, which were not included due to poor detection.

The XRD analysis showed quartz (SiO_2) to be the dominant mineral in all samples together with various clay minerals (containing potassium, magnesium, silicon, aluminum, oxygen, and hydrogen), K-feldspar ($KAlSi_3O_8$), calcite ($CaCO_3$), and gypsum ($CaSO_4\ 2H_2O$) present in lesser amounts. The mineral dolomite ($CaMg(CO_3)_2$), various iron oxides, halite, and polyhalite may also be present in some of the samples in very small amounts. The XRD analysis combined with examination of bivariate cross plots of the elemental data allowed the determination of which elements were associated with the various mineral phases (Table 1). These were as follows: silicon (associated with quartz, feldspar, and clays); potassium (associated with clays, feldspar, and polyhalite); calcium (associated with calcite, gypsum, and dolomite); iron (associated with clays and iron oxides); titanium (associated with clays and iron oxides); chlorine (associated with halite); sulfur (associated with gypsum

Forensic Geoarchaeology, Table 1 XRF analysis results for sediment samples collected from Horse Rock Ruin, Monticello Ranger District, Manti-La Sal National Forest, San Juan County, Utah

		Associated with									
Element	Comment	Quartz	Feldspar	Clays	Polyhalite	Halite	Gypsum	Dolomite	Calcite	Iron oxides	Carbonates
Al (aluminum)	Poor detection										
Zr (zirconium)	Poor detection										
Si (silicon)	Oxide calculated	x	x	x							
K (potassium)	Oxide calculated		x	x	x						
Ca (calcium)	Oxide calculated						x	x	x		
S (sulfur)	Oxide calculated				x		x				
Cl (chlorine)	Oxide calculated					x					
Mn (manganese)	Oxide calculated	x	x								
Ti (titanium)	Oxide calculated			x						x	
Fe (iron)	Oxide calculated			x						x	
Zn (zinc)	Oxide calculated										x
Sr (strontium)	Oxide calculated			x			x		x		
Rb (rubidium)	Oxide calculated		x								
Cu (copper)	Variable										
Br (bromine)	Variable										
As (arsenic)	Variable										

and polyhalite); zinc (associated with carbonates); strontium (associated with clays, calcite, and gypsum); rubidium (associated with feldspar); and manganese (associated with quartz and feldspar).

Further examination of the bivariate plots of the elemental data showed that the sediment samples from the various sample groups tended to cluster in relatively tight configurations. This clustering is caused by the degree of similarity within each sample group. Examination of the bivariate plots for different elements demonstrated that the degree, or tightness, of clustering was best demonstrated by the elements calcium, potassium, chlorine, and sulfur. All these elements were present in mineral phases associated with the soluble portion of the sediment (calcite, gypsum, and polyhalite). These minerals precipitate within any pore space, and one would expect their abundance to be controlled primarily by the groundwater chemistry of the specific location from which they were collected. The abundance of the four elements (calcium, potassium, chlorine, and sulfur) was used in a computerized multivariate statistical analysis to determine the degree of similarity among the various sample groups.

The four variables (calcium, potassium, chlorine, and sulfur) were converted to standardized scores by subtracting the mean of a variable from each value for that variable and dividing the result by the standard deviation of that variable. These standardized scores were the basis for calculating a Euclidean distance between each pair of the 85 sediment samples analyzed. These Euclidean distances represented how like or unlike each pair of samples was in terms of the four variables measured. Because their values were first standardized, each of the four variables contributed equally to the distance measurement.

Results of the statistical analysis clearly indicated that the sediment adhering to the interstices of the coiled and plaited baskets was most similar, if not identical, to the sediment samples from the Horse Rock Ruin site and contiguous alcove. The sediment samples from the other alcoves and open sites were clearly dissimilar. On 17 January 1986, Shumway pleaded guilty to the ARPA violations in federal court in Salt Lake City, Utah.

Tin Cave litigation

In a second and, in some ways, more egregious case (USA vs. Ralph Cortiana), R. Cortiana was indicted in 1987 for attempting to sell a Native American infant mummy to an undercover federal agent for $35,000. Cortiana had looted the mummy with a wealth of accompanying grave goods from Tin Cave on the Tonto National Forest near Roosevelt Lake, northeast of Phoenix, Arizona (Donahue and Cooke, 1987).

At the request of the US Attorney's office in Phoenix, the author and the late R. L. Andrews examined the mummy and associated grave goods and determined that they were either of Hohokam or Salado ascription. Additionally, a radiocarbon assay was processed on a fragment of deerskin (*Odocoileus* sp.) associated with the mummy. This assay yielded a date of $1350 \pm 25\,^{14}C$ yr BP.

In order to obtain a definite link between the despoiled remains and the suspected site of vandalism, sediment samples adhering to the body and the mummy's grave goods were removed, and three additional sediment samples were collected by the author from the floor of Tin Cave itself. Each Tin Cave sample was collected from a different location within the cave, including the alleged burial pit, in order to ascertain if different portions of the surface evidenced distinctive geochemical signatures (Donahue and Cooke, 1987).

The samples initially were examined via optical binocular microscopy. Microscopic examination revealed that the larger size fraction of each sample consisted of highly variable amounts of organic detritus and rock fragments. In order to eliminate this highly variable coarse material, the samples were dry-sieved, and the fraction containing particulate sizes smaller than 63 μ – that is, 63 micrometers (μm) or 0.063 mm – was retained for further analysis. Two analytic methods were then employed to characterize the samples.

Mineral composition of the samples was determined by X-ray diffraction (XRD) analysis. The diffraction analysis was again run on a General Electric XRD-5 unit with a copper X-ray tube at 35 kV and 15 mA. Medium resolution slits were used, and a scanning rate of 2.2 was employed. Bulk mineralogy was determined from a 63 μ-or-smaller sample that was mixed with an aluminum metal internal standard and ground to a finer grain size with a mortar and pestle. Each sample was sifted onto a Vaseline-coated glass slide and was then X-rayed using standard analytical procedures. Clay mineralogy was determined by examining an organic-free, oriented mount of a less than 3 μ size fraction from each sample. The organics were removed from each sample by digestion in sodium hypochlorite. The less than three micron size fraction was obtained from each sample by gravity settling in an aqueous medium. A slurry of this <3 μ size fraction was then placed on a glass slide. After drying, the sample was saturated with ethylene glycol and X-rayed using standard procedures. The samples were then heated to 300 °C and 500 °C, with X-ray patterns obtained after each heating.

Chemical composition of the samples was determined by X-ray fluorescence (XRF) analysis. The fluorescence analysis, which as noted above identifies elements heavier than aluminum, was run on the same Tracor Northern Spectrace 440 unit. Splits of the <63 μ size samples were treated by ignition of the sample to 1000 °C in order to decompose organic and inorganic carbon. During ignition, weight loss of each sample was determined at 110 °C, 550 °C, and 1000 °C. These values indicate the mass of absorbed water, organic carbon, and inorganic carbon content, respectively, that had been lost through ignition. Each sample was then crushed in a mortar and pestle and transferred to sample cups covered with Mylar. For XRF analysis, two scans were run for each sample, one at 20 kV and 0.1 mA and the other at 35 kV and 0.1 mA, each with a thin molybdenum window to block out most of the direct signal from the molybdenum X-ray tube. The spectrum at each setting was recorded for 200 s. The individual spectral lines for each element were identified, and their intensities were recorded. United State Geological Survey standards were also analyzed to provide calibration coefficients for the intensity data in order to determine element concentrations. These concentrations were then normalized to 100 % of the <63 μ size ignited sample.

Analysis by XRD determined that the following minerals were present in all four samples: quartz, calcite, feldspar, apatite, whewellite, and the clay minerals, smectite, illite, and chlorite. After identification of mineral phases, the amount of each mineral was estimated from the intensity of major peaks and the internal standard method of calculation. Correction factors to convert from peak intensities to mineral percentage were determined by running pure mineral/aluminum mixtures. The resulting percentages were normalized to 100 %. Because no pure sample of the rare mineral whewellite (hydrous calcium oxalate or $CaC_2O_4 \cdot H_2O$) was available, a ratio value was determined by comparing the whewellite peak to the aluminum internal standard peak. In addition, clay mineral percentages were determined by using clay standards to derive correction factors in order to calculate the amount of each clay mineral.

Although some difference occurred in the percentage values, the mineral composition of all four samples was the same. All of the samples contained quartz, feldspar, calcite, and the clay minerals, smectite, illite, and chlorite. This is not surprising as these minerals are commonly found in sediments. Detailed analysis of the clay minerals, however, revealed several distinctive characteristics that all four samples had in common.

The dominant clay mineral assemblage was a mixture of illite and smectite. Lesser amounts of chlorite were present. No kaolinite, a relatively common clay mineral, was detected in any of the samples. During XRD analysis of the bulk sample (<63 μ fraction) from each of the four samples, the position of the smectite 001 reflection suggested that this clay predominantly contains calcium rather than sodium in the exchange positions. This indicates a calcium-rich environment for both the Tin Cave sediments and the sediment collected from the mummified infant.

In the detailed clay mineral XRD analysis (<3 μ samples) of all four sediments, the smectite also showed unusual behavior when it was heated. Smectite, a swelling clay, usually loses its water and collapses when heated to 300 °C for 1 h. In the four samples, however, the smectite only partially collapsed at 300 °C. Complete collapse of the smectite occurred only upon additional heating to 500 °C. Although the precise cause for this unusual behavior was not determined, it is very likely that it is identical in all four samples. This further suggests a common source for all four samples.

The occurrence of apatite in all of the samples is also suggestive of a common origin for all of them. Apatite is frequently found in association with organic material, especially bones and teeth, and thus it can be expected in the Tin Cave setting. Most unusual, however, is the occurrence of the mineral whewellite, which is extremely rare. We have found only two documented occurrences in the USA. These are in concretions in the Devonian Huron black shales of Ohio and in some modern peat bogs located in Florida. Whewellite appears to be associated with the alteration of woody organic detritus in a neutral to basic, calcium-rich environment.

The XRF analysis detected the presence of the following elements: silicon, calcium, aluminum, iron, potassium, manganese, titanium, zinc, strontium, copper, and rubidium. Examination of both the mineral and chemical data makes it possible to assign the elements and their oxides to the minerals in which they occur. The chemical data, coupled with their associations, provided the basis for a statistical analysis of the Tin Cave and mummified infant soil samples. In particular, the association of the trace elements (Rb, Sr, Zn, Cu, K, Ti, Fe, and Mn) with the clay minerals formed the basis for generating a series of ratios to be used in statistical analysis. Once again, Euclidean distances were calculated between the samples, and the results conclusively showed that the soil adhering to the mummified infant was essentially identical to the samples from Tin Cave.

Cortiana elected not to plead out in this case, though the defense inexplicably stipulated to the damning geoarchaeological evidence. He was eventually found guilty in the first ARPA case involving forensic sedimentology to be argued before a jury.

Site 206 litigation

Since these first forays into the use of forensic sedimentology both involved closed sites (i.e., a cave, rock-shelter, or architectural alcove), it was decided that the logical extension of this line of evidence collecting and analysis was to employ the same protocols in a case involving open site vandalism. This posed special problems that required the use of additional highly sensitive techniques not employed in earlier cases.

The suspect in the first open-site case, W. E. Sherman, was alleged to have removed artifacts from a Pueblo-style aboriginal surface structure on an archaeological site designated AR-03-06-07-206 (hereafter called Site 206) located in the Gila National Forest in New Mexico (Donahue et al., 1990). Sherman claimed the seized materials derived from private land located very close to the suspected locus of looting. This parcel of property contained two prehistoric sites (hereafter called Sites 1 and 2) which had also been looted. Later, Sherman changed his story and suggested the seized material came from a third site also located on private land a considerable distance from Site 206. This site was designated XSX.

In order to tie Sherman's artifacts to Site 206, the suspected location of the theft, evidence was sought and scrutinized from four compositional classes of samples. These included bedrock samples, soil samples, daub samples, and fired aboriginal potsherds. Bedrock and soil samples were provided by the USDA Forest Service and/or collected by the author from a series of archaeological locations within or adjacent to the Gila National Forest, New Mexico. Soil was also removed from the hand tools and clothing found in Sherman's possession and possibly used in the vandalizing of Site 206. Finally, soil was collected from the inner surfaces of ceramics also found in Sherman's possession, and the ceramics were seized as well.

The soil samples specifically include four samples manually collected by USDA Forest Service personnel from a vandal's pit, which was designated as Hole 6 and located within an aboriginal structure on Site 206. One sample derived from the subfloor of floor feature #7, while three samples were extracted from the modern ground surface and at depths of 30 cm and 61 cm below the modern ground surface of Hole 6, respectively.

Soils collected by the author from Site 206 included three samples from the same room sampled by USDA Forest Service personnel, but these were obtained from the buried undisturbed walls rather than the mechanically turbated fill of this structure. The samples were manually removed by trowel at depths of 50–60 cm, 60–70 cm, and 80–90 cm below modern ground surface, respectively.

The USDA Forest Service also provided soil samples from three other locations, including one each from Site AR-03-06-07-205 (hereafter called Site 205) on federal property and two sites designated Sites 1 and 2 on private land. The USDA Forest Service Site 205 sample was collected from an aboriginal structure fill at a depth of 20 cm below modem ground surface as were the general soil (i.e., non-structure fill) samples from Sites 1 and 2. In addition, the author collected two samples from the site designated as XSX and located on private land directly adjacent to the Gila National Forest. These samples were taken via trowel from gravel fill at depths of 10 cm and 14 cm below modern ground surface, respectively.

The samples provided by the USDA Forest Service from Sherman's hand tools and clothing include soil samples from an ice pick, a shovel, and a pick ax. The sample from the clothing was principally derived from the pockets of a pair of coveralls.

The last suite of soils included three samples provided by the USDA Forest Service representing scrapings of fill derived from the inner surfaces of aboriginal ceramic vessels found in the possession of the alleged pothunter.

A number of daub samples were collected by the USDA Forest Service personnel and the author; they include two specimens from Site 206, one from Site 1 and one found in the possession of the alleged pothunter.

Finally, the ceramic samples provided by the USDA Forest Service included two conjoining ceramic sherds from Site 206. The two sherds conjoin a third sherd recovered in the possession of the alleged pothunter.

Six different techniques were employed on the samples from New Mexico. These included:

1. Grain size analysis (using sieves for the sand-sized fraction of each sample and Coulter counter analysis for the silt- and clay-sized fractions)
2. Flame emission spectrophotometry to determine abundances of exchangeable and extractable metallic

cations of both major and trace elements including barium, cadmium, calcium, cobalt, copper, iron, lead, magnesium, manganese, nickel, potassium, sodium, strontium, and zinc
3. Flow injection and high-performance liquid chromatography to determine the type and amount of organic material present in the samples
4. Water leach atomic absorption (WLAA) via a Varian SpectrAA 300 unit to determine the type and amount of more water-soluble cations present in the samples
5. X-ray diffraction analysis via a General Electric XRD-5 unit with a copper X-ray tube at 35 kV and 15 mA to determine bulk mineralogy for five mineral phases (quartz, feldspar, orthoclase, microcline, and plagioclase)
6. Computer-controlled scanning electron microscopy (CCSEM)

CCSEM is an analytic technique used to acquire information on the size, shape, and both chemical and mineral composition of individual sediment grains in a soil sample in an automated manner. It is performed by combining three analytic tools under the control of a computer: (1) the scanning electron microscope (SEM), which is widely used in materials science because of its high resolution and depth of field; (2) energy dispersive X-ray spectroscopy (EDS), which adds to the SEM the extra dimension of X-ray microanalysis; and (3) the electron beam control via the digital scan generator, which allows rapid measurement of the size and shape of individual soil grains found in the SEM image.

Finally, thin sections were prepared from the two conjoining ceramic sherds and examined with a Leitz petrographic microscope. This examination allowed characterization and identification of coarser-grained temper (inclusions) as well as characterization of both paste and void space within each sherd.

After a somewhat lengthy jury trial in which, for the first time, the defense produced its own expert witness, Sherman was convicted on all counts.

More recent cases

Since these initial cases in forensic sedimentology, the author and his associates have been involved in a series of ARPA prosecutions, all of which have resulted in plea bargains or convictions. As in the three cases summarized above, in each instance, the accused had vandalized a site or sites on federal property. Additionally, all claimed the purloined artifacts were ethnographic in origin and derived from nearby private land, or they denied culpability completely. Space and time constraints preclude any in-depth discussion of the post W. E. Sherman cases; however, certain salient facts about several of them are worth noting. In the celebrated and highly publicized Polar Mesa case, actually a series of many separate ARPA prosecutions, a group of individuals was charged with vandalizing a number of closed and open localities in the Manti-La Sal National Forest in Utah. The author's participation in these prosecutions was fourfold. Together with the late R. - L. Andrews, we analyzed, described, and validated the prehistoric age of the archaeological materials recovered from two closed sites (42GR383 and 42ML3169) and/or seized from the indicted suspects. Subsequently, the author personally collected sediment samples from one of the vandalized closed site localities and, finally, oversaw the processing, analysis, and interpretation of sediment recovered from the seized artifacts as well as those collected from the location of the theft (Adovasio and Andrews, 1990; Donahue and Adovasio, 1986).

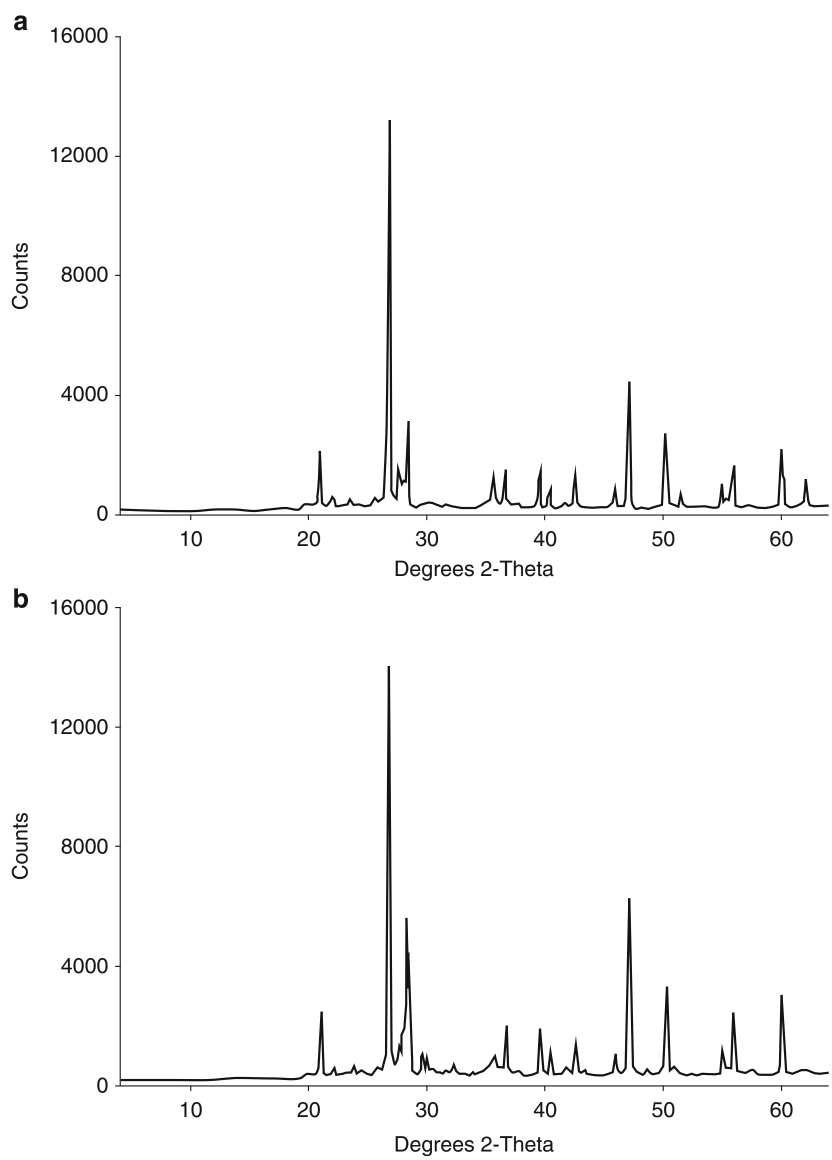
The mineralogical and chemical analysis conducted for these prosecutions involved XRD, CCSEM (with 500 or 1000 particle samples), and water leach chemical analysis employing a SpectrAA 300 Atomic Absorption unit for dissolved cations and a Dionex 2120i Ion Chromatograph for anions. These analyses were performed on two sediment samples from each site and 18 sediment samples from seized artifacts. The results of these analyses indicated that the sediments from both sampled closed sites on Polar Mesa could be readily distinguished from one another and, further, that 12 of the seized artifacts could be matched to site 42GR383. One artifact was matched with site 42ML3169 while another most closely corresponded to that locality. The sediment from four other artifacts derived from other, unsampled, looted localities. As a result of these analyses, a series of plea bargains or convictions were obtained.

In USA versus Tony Maschler and John D. Price, the accused, two Coconino County Sheriff's deputies, allegedly vandalized several locations within Kinnikinnick Pueblo (AR-03-04-05-45) on Anderson Mesa within the Coconino National Forest, ca. 30 miles southeast of Flagstaff, Arizona (Cooke and Adovasio, 2000). In this case, 24 sediment samples of three types were scrutinized: 13 of these derived from tools, gloves, or clothing seized from the suspects; 3 came from seized *Conus* sp. shell "tinklers" (small perforated and truncated cone-shaped shell ornaments); and 7 derived from vandalized rooms at the Pueblo. Analytical methodologies included manual scanning electron microscopy (MSEM) of aggregated particulate using an SEM equipped with an EDS and the capacity to examine the sediment in BEI (backscatter electron imaging) mode. Selected sediments were also subjected to bulk mineralogy analysis via XRD with a Phillips XR6 3100 XRD unit, and then the same samples were subjected to sequential chemical leaches for carbonates, sulfates, and iron oxide/hydroxide. The clay-sized samples from the sequential leaches were also examined for clay mineralogy via XRD.

The results of all these analyses were mutually supportive and conclusively linked the two suspects to the seized artifacts and the location of the vandalism. Both submitted guilty pleas.

The last case to be summarized here, USA versus Jerry Lee Young, represents one of the boldest examples of site vandalism on a grand scale (Adovasio and Illingworth, 2001; Cooke et al., 2001). Young operated a for-profit museum in Jackpot, Nevada, which contained thousands of artifacts, many of which were allegedly removed from federal property in at least three states. In August of 1998, the author and J. E. Thomas collected sediment samples from three of the vandalized properties and subsequently removed sediments from artifacts found in seven seized display cases. Also collected were sediments adhering to a bucket confiscated from Young's property. Young claimed that the bucket was used to mix cement.

In total, 20 samples were analyzed in two stages. In stage I, sediment from one of the vandalized locations was compared to sediment from the seized bucket. XRD was employed to determine crystalline phases in the samples, and CCSEM with EDS was used to determine the chemistry of individual sediment particles. A third sample, also from the seized bucket, was examined via MSEM with EDS to determine if it was cement as claimed by the suspect. In the second stage, the same analytical techniques employed in stage I were used with sediments extracted from selected seized artifacts from the Young Museum. Once again, the results of all of these analyses were conclusive. Sediments from the vandalized sites were readily distinguishable from one another. The bucket samples were not cement and directly linked Young to one of the vandalized sites; five



Forensic Geoarchaeology, Figure 3 XRD plots from the Bob's Cave case, showing: (**a**) the relative frequency of mineral components in a sediment sample from one of the looted localities and (**b**) the relative frequency of mineral components in sediment removed from a bucket found at Young's house. Peaks are unlabeled as to mineral phase represented, but the figure intends to demonstrate only the remarkable similarity between the two sample plots.

of the artifact-derived samples were congruent with an origin in one of the vandalized sites (Figure 3). Young was subsequently convicted of multiple ARPA violations.

Summary

According to local authorities, the successful prosecution of the cases summarized above had an immediate, if perhaps only temporary, dampening effect on pothunting activities in their respective areas. Unfortunately, they also probably led to increased attention by pothunters and dealers to such hitherto ignored considerations as the thorough cleaning of looted artifacts. Tying soil residues to site earth may become more challenging in the future, but the science of proving looted objects to be ancient as opposed to recent ethnographic items and documenting their origin will continue to offer avenues to conviction for illicit collectors. The basic utility of the forensic techniques discussed here remains valid and valuable in the prosecution of antiquities theft.

All of the cases discussed here clearly demonstrate the extreme resolution possible with forensic geoarchaeological analyses, generally, and forensic sedimentology, in particular. In so doing, they also provide in many cases – especially where no other probative information may be available – a very potent weapon in the armamentarium of law enforcement agents.

In retrospect, certain conclusions should be stressed. First, as with the seminal investigations at Meadowcroft Rockshelter, the collection of samples to be retrieved, analyzed, and compared in ARPA prosecutions must be rigorous and very carefully executed. Twenty-five years of experience have demonstrated that mechanically or biologically turbated sediments frequently produce misleading or erroneous results when compared to samples from carefully excavated, undisturbed contexts. Thus, as stressed previously (Adovasio et al., 1991), it is critical that "fresh" (i.e., newly cut) surfaces of walls, profiles, and "floors" be sampled by trained professionals intimately familiar with the nuances of depositional processes (Figures 4 and 5). Second, it is clear from the foregoing that these kinds of laboratory analyses are very time consuming and require sophisticated instrumentation and highly experienced personnel. Hence, they are invariably relatively expensive and should be employed judiciously. Nonetheless, it is clear that the expenditures of time and money have been justified by the success rates in these types of ARPA prosecutions. Third, though the basic field protocols and attendant laboratory analyses have

Forensic Geoarchaeology, Figure 4 A USDA Forest Service employee "facing" a looter's hole in preparation for sampling.

Forensic Geoarchaeology, Figure 5 Clear, labeled stratigraphic sequence within a looter's hole ready for geoarchaeological sampling.

remained strategically constant over the past 25 years, the tactics of recovery and analysis have evolved exponentially. Instrumentation in both field and laboratory contexts is now many technological generations removed from what was employed in 1985–1986, and, if anything, the precision and reliability has only increased. So has the portability of some very potent analytical tools. For example, now there are handheld XRF devices which function essentially like hair dryer-sized implements that permit analysis of sediments and sediment profiles *in the field* with virtually the same accuracy and reliability as tabletop instruments.

It is pertinent to reiterate (and time has corroborated) the author's final comments in Adovasio and Andrews (1990) which described the earliest applications of forensic sedimentology in ARPA prosecutions. It is now possible to detect the equivalent of "fingerprints in the sand," and this capability has become a powerful weapon in the unfortunately unending conflict with those who would destroy the archaeological legacy, not just of Native Americans, but of all people of every cultural heritage.

Despite the proven probity of forensic geoarchaeology in the cases cited above, these techniques have not become common in North America or anywhere else. The author has been the principal investigator of all such cases prosecuted to date in North America. The failure of forensic geoarchaeology to encourage a larger audience of service providers may be attributed to several causes. (1) Thus far all but one of its applications have been in the arcane arena of ARPA cases – a sphere of law enforcement known little, if at all, outside of its practitioners. (2) Even to the initiated, forensic geoarchaeology, it seems overly complex, time consuming, and therefore daunting to many potential practitioners. This is often the case in situations where carefully collected data by qualified, credentialed archaeologists is available for potential analysis. (3) The application of forensic geoarchaeological field and laboratory protocols is not inexpensive. This is compounded by the fact that few field-workers, even in archaeology, have the requisite battery of skills to assess and prepare a site for sampling, and almost none exist in traditional law enforcement agencies. Additionally, the analytical equipment needed for geoarchaeological research is not cheap to acquire and maintain, and it requires expertise to operate and interpret the results of analysis. Perhaps, as the oftentimes spectacular results of geoarchaeological analysis in forensic applications become better known, the problems of poor participation will diminish.

Bibliography

Adovasio, J. M., and Andrews, R. L., 1990. The Horse Rock Ruin (42SA10550) *Basketry Cache: An Unparalleled View of Regional Pueblo Perishable Technology*. Paper presented at the 55th annual meeting of the Society for American Archaeology, Las Vegas, April 18–22, 1990.

Adovasio, J. M., Donahue, J., Cooke, G. A., and Quigley, M. N., 1991. *Forensic Geoarchaeology: Three Case Studies*. Paper presented at the 56th Annual Meeting of the Society for American Archaeology, New Orleans, April 23–28, 1991.

Adovasio, J. M., and Illingworth, J. S., 2001. *Report on the Artifact Technology for USAO No. 01-015-S-BLW, U.S. v. Jerry Lee Young*. Manuscript on file, Mercyhurst Archaeological Institute, Mercyhurst University, Erie.

Cooke, G. A., and Adovasio, J. M., 2000. *Report on the Forensic Sedimentology Analysis of Selected Soil Samples for USAO No. 2000R02203: U.S. v. Tony Maschler and John D. Price*. Manuscript on file, Mercyhurst Archaeological Institute, Mercyhurst University, Erie.

Cooke, G. A., Adovasio, J. M., and Illingworth, J. S., 2001. *Forensic Sedimentologic Analysis of Sediment Samples, U.S. v. Jerry Lee Young*. Manuscript on file, Mercyhurst Archaeological Institute, Mercyhurst University, Erie.

Donahue, J., and Adovasio, J. M., 1986. *Notes on the Analysis of the Horse Rock Ruin (42SA10550) Basket Cache Sediments*. Manuscript on file, Department of Anthropology, University of Pittsburgh, Pittsburgh.

Donahue, J., and Cooke, G. A., 1987. *Mineral, Chemical, and Statistical Analysis of Soil Samples from Tin Cave, AR-03-12-06-104, Arizona, and from a Mummified Infant*. Manuscript on file, Departments of Anthropology, Geology and Planetary Sciences, University of Pittsburgh, Pittsburgh.

Donahue, J., Adovasio, J. M., Cooke, G. A., and Quigley, M. N., 1990. *Report on the Mineralogical, Chemical and Statistical Analyses of Selected Soil, Daub and Pottery Samples from the Gila National Forest, New Mexico*. Manuscript on file, Departments of Anthropology, Geology and Planetary Sciences, University of Pittsburgh, Pittsburgh.

Cross-references

Electron Probe Microanalyzer
Scanning Electron Microscopy (SEM)
X-ray Fluorescence (XRF) Spectrometry in Geoarchaeology

FOURIER TRANSFORM INFRARED SPECTROSCOPY (FTIR)

Francesco Berna
Department of Archaeology, Simon Fraser University, Burnaby, BC, Canada

Synonyms

FT-IR; Fourier transform infrared spectroscopy; Infrared spectroscopy

Definition

FTIR (Fourier transform infrared spectroscopy) is an instrumental technique used to identify the functional groups present in organic and inorganic compounds by measuring their absorption of infrared radiation over a range of wavelengths (Smith, 2011; Margaris, 2014). The FTIR method first collects an interferogram of a sample signal using an interferometer, and then it performs a Fourier transform (a mathematical algorithm) on the interferogram to obtain the infrared spectrum. An FTIR spectrometer, thus, collects and digitizes the interferogram, performs the Fourier transform, and displays the FTIR spectrum. Modern FTIR spectrometers obtain infrared spectra in absorption, total and diffuse reflectance, attenuated total reflectance (ATR), and photoacoustic modes from solid, liquid, or gaseous samples. Typically, only tens of micrograms of a sample are required, and spectrometers can be coupled to microscopes for the analysis of particles as small as 10 μm in diameter. Infrared spectrometers are also available as portable devices and can therefore be used reliably and conveniently on-site.

The Uses

Infrared spectroscopy can identify and characterize both inorganic and organic materials of geoarchaeological interest (Weiner, 2010). This analytical technique, in fact, has the major advantage of being able to identify both crystalline and amorphous minerals (e.g., quartz and opal) as well as many organic materials, including crystalline and "amorphous" inorganic compounds (such as silicates, carbonates, phosphates, sulfates, and nitrates) and organic compounds (such as fatty and humic acids, oxalates, proteins, lignin, cellulose, and graphite). FTIR is very sensitive to compositional and structural changes such as crystallinity and atomic disorder. It is thus particularly useful for the identification of authigenic minerals; the study of biomaterials such as bone, shells, and endo- and exoskeletons of cell tissues (e.g., phytoliths) and microorganisms; and the characterization of charcoal and bone collagen. FTIR is also uniquely suitable for the identification and characterization of pyrogenic calcite and high-temperature silicates; thus, it can be extremely useful for the reconstruction of ancient pyrotechnological activities. FTIR is therefore a very valuable technique for the identification and characterization of the geogenic and biogenic components of the archaeological record, stratigraphic correlations, and the reconstruction of human activities, diagenetic transformations, and site formation processes. By using FTIR microspectroscopy, which couples an FTIR spectrometer to a petrographic microscope, it is possible to perform FTIR analysis directly upon thin sections of intact archaeological materials and sediments, thus allowing the integration in real time of micromorphological, petrographic, chemical, and mineralogical analyses (Goldberg and Berna, 2010). In turn, the data produced by integrating soil micromorphology and FTIR microspectroscopy can yield high-resolution, contextualized information about technology, activities, and site formation processes.

Bibliography

Goldberg, P., and Berna, F., 2010. Micromorphology and context. *Quaternary International*, **214**(1–2), 56–62.

Margaris, A. V., 2014. Fourier Transform Infrared Spectroscopy (FTIR): applications in archaeology. In Smith, C. (ed.), *Encyclopedia of Global Archaeology*. New York: Springer, pp. 2890–2893.

Smith, B. C., 2011. *Fundamentals of Fourier Transform Infrared Spectroscopy*, 2nd edn. Boca Raton, FL: CRC Press.

Weiner, S., 2010. *Microarchaeology: Beyond the Visible Archaeological Record*. New York: Cambridge University Press.

Cross-references

Site Formation Processes
Soil Micromorphology

G

GAS CHROMATOGRAPHY

Ruth Ann Armitage
Department of Chemistry, Eastern Michigan University, Ypsilanti, MI, USA

Synonyms

Gas-liquid chromatography (GLC); Gas-solid chromatography (GSC)

Definition

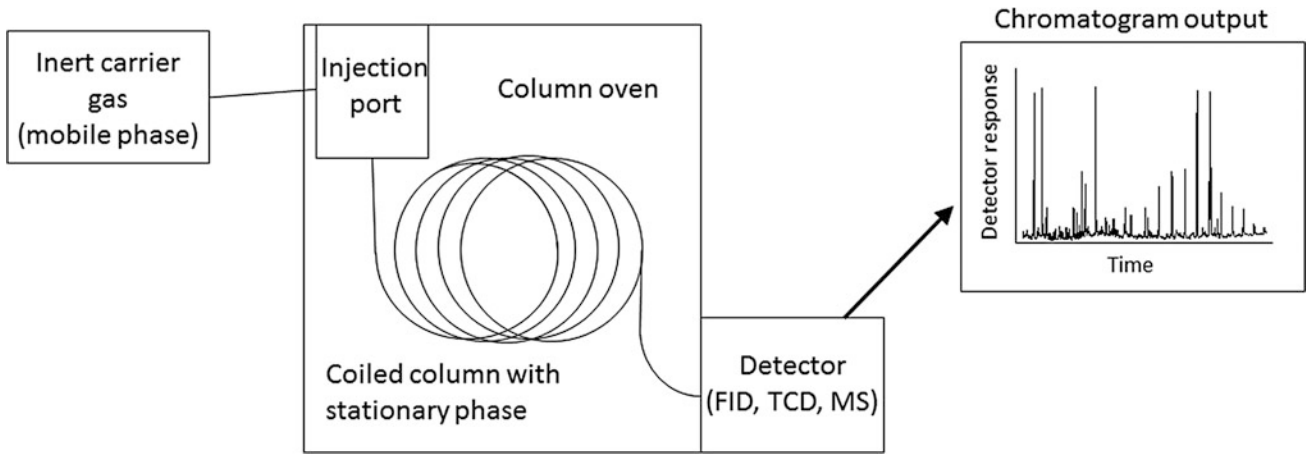
Chromatography is a method of separating mixtures based on how the molecules interact with an immobilized stationary phase and a mobile phase. It was invented in 1906 by Russian botanist Mikhail Tswett for separating various pigments in plants (thus the derivation of the name: *chroma* = color, *graph* = writing). Separation occurs because each component of the mixture undergoes different intermolecular interactions with the stationary phase through physical adsorption or interactions between the uneven distributions of charge in some molecules, called *dipoles*. Components that interact more strongly with the stationary phase are slowed in relation to those that interact less or not at all. In gas chromatography (GC), the separation occurs in the gas phase. The mixture is propelled by an inert gas, usually helium or hydrogen, as the mobile phase. In *gas-solid chromatography*, the stationary phase is a solid like alumina, where separation occurs due to differential surface adsorption. In *gas-liquid chromatography*, an immobilized liquid serves as the stationary phase; in this case, separation is effected by dipole interactions.

Background

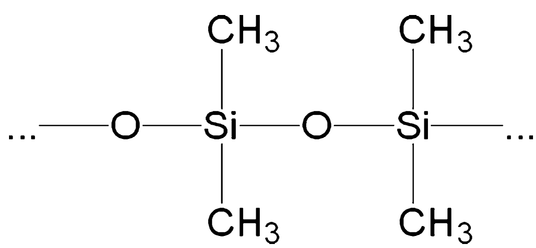
A schematic for a basic gas chromatograph is shown in Figure 1. The instrument consists of a heated injection port, which converts a liquid sample mixture into vapor. Samples may be injected by hand using a syringe or using an autosampler. In either case, the liquid sample is contained within a syringe equipped with a sharp needle, which is used to pierce a polymer septum. When the liquid is injected into the heated port, it flashes to a vapor and is swept by the mobile phase carrier gas into the column containing the stationary phase. *Packed columns* consist of stainless steel tubing filled with finely divided silica-based material or alumina. A packed column for gas-liquid chromatography (GLC) has the liquid stationary phase chemically bonded to the packing material. *Capillary columns* are open tubes (and are sometimes called *open tubular columns*), the interior wall of which supports the stationary phase. *Porous layer open tubular* (PLOT) capillary columns are used in gas-solid chromatography, while *wall-coated open tubular columns* are used in GLC applications. One common liquid stationary phase is the highly nonpolar (meaning no uneven distribution of charge is present) polymer polydimethylsiloxane, made up of the repeating structure shown in Figure 2. In addition to the chemical bonding between the stationary phase and the column material, the stationary phase material is also usually cross-linked, wherein bonds are formed between the polymer chains for added mechanical stability. In a mixture of molecules with varying polarity, those that are most nonpolar (e.g., straight-chain hydrocarbons) will interact most strongly with this nonpolar stationary phase, while those that are less so (e.g., aromatic compounds like benzene) will interact less strongly. The result is that the aromatic compounds *elute* or are passed out of the column more rapidly than are the others.

At the outlet of the column, separated components pass into a detector, a device that produces a change in electrical signal when something other than carrier gas is present. A graph of detector response over time is called a chromatogram; components are shown as "peaks" in

A.S. Gilbert (ed.), *Encyclopedia of Geoarchaeology*, DOI 10.1007/978-1-4020-4409-0,



Gas Chromatography, Figure 1 Box diagram of a typical gas chromatograph.

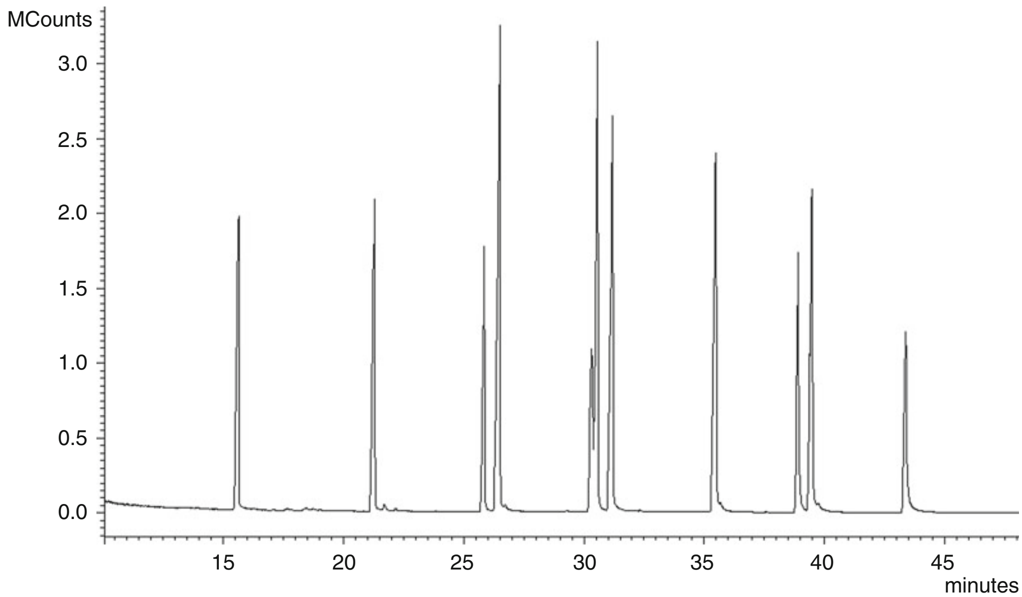


Gas Chromatography, Figure 2 Two dimethylsiloxane units of a polydimethylsiloxane chain used as a nonpolar GC stationary phase.

the chromatogram, representing the Gaussian distribution of interactions between the component and the stationary phase. An example chromatogram is shown in Figure 3. The area under the peak is generally proportional to the concentration of that specific component in the mixture. Thus, gas chromatography provides a qualitative picture of the nature of the mixture, and with appropriate standards, a quantitative measure of how much of each component is present.

The amount of information that can be obtained from gas chromatography is determined by the nature of the detector. Thermal conductivity detectors (TCDs) monitor the transfer of heat across a set of resistors in the column effluent. The difference between the thermal conductivity of carrier gas alone and that of the eluted compounds is measured and converted into an electrical signal that is then plotted over time. TCDs are not very sensitive (i.e., they do not yield a large change in signal with small changes in the amount of analyte present), but they are rugged and nondestructive and can be used for noncombustible substances like water and carbon dioxide. A flame ionization detector (FID) is a very sensitive detector for GC, but it provides no identifying molecular information about the components being eluted. In an FID, each component is combusted in an air-hydrogen flame, producing charged species called *ions*; these ions then produce a measurable change in voltage at a set of charged plates above the flame. TCDs and FIDs are general-use detectors for gas chromatography. Other detectors including electron capture detectors and flame photometric detectors are specific to certain elements or functional groups, providing *selectivity*, or a reduction in interferences, for GC analyses. For all of these detectors, compounds can be identified in the chromatograms based only on a comparison of the retention time (how long the compound takes to reach the detector) of each component compared to reference compounds separated under the same conditions.

A mass spectrometer can be used as a GC detector to identify the components based on more than just reference retention time. This "hyphenated method," called gas chromatography-mass spectrometry, is used for nearly all applications of gas chromatography in analyses relevant in geoarchaeology. In a mass spectrometric detector, the effluent from the column passes into a vacuum chamber where the components are ionized while they remain in the gas phase. This is typically done by a stream of energetic electrons produced at a filament. *Electron impact ionization* imparts sufficient energy to the eluted molecules to remove electrons, leaving energetically unstable *cations* (positively charged species) that typically fragment to yield a pattern called a *mass spectrum* for each component of the mixture. A mass spectrum provides a molecular fingerprint for identifying the components, often using a comparative database like the NIST/EPA/NIH Mass Spectral Library (NIST08) published by the National Institutes of Standards and Technology's Mass Spectrometry Data Center. In gas chromatography-combustion-isotope ratio mass spectrometry (GC-C-IRMS), an additional step between separation and mass spectrometry involves a combustion chamber where individual compounds are converted to carbon dioxide



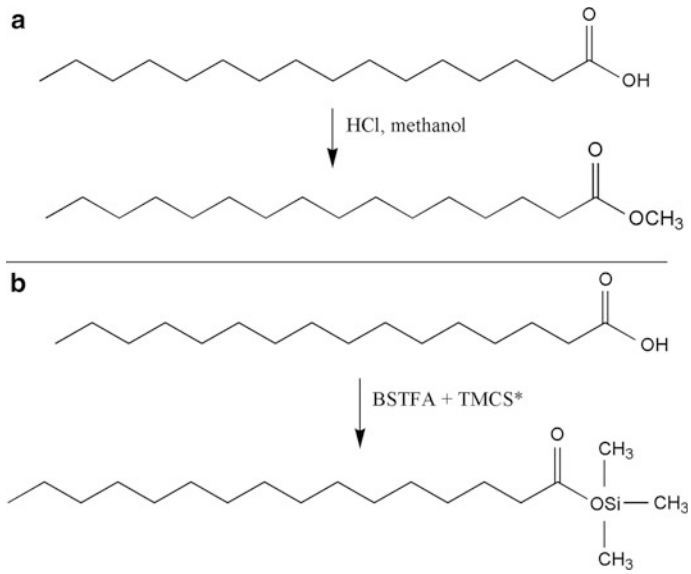
Gas Chromatography, Figure 3 Gas chromatogram of a standard mixture of fatty acid methyl esters. Each peak corresponds to a different compound. The identity of the compound is determined by retention time, which is observed on the x-axis (time in minutes), as well as the mass spectrum if a mass spectrometer is used as the detector. The first peak, around 15 min, corresponds to molecules of the compound that interacts the least with the stationary phase, exiting the column and entering the detector first. The last peak reflects the compound that is retained most strongly by the stationary phase and therefore elutes last. In this example, the fatty acid methyl esters are separated in order of chain length, where the shortest is fastest and the longest is slowest. Unsaturated compounds (those with one or more double bonds, like those in the peak at 25.5 min) elute shortly before saturated ones (like those in the peak at 26.5 min).

(and nitrogen oxides in the case of amino acids, which must then be reduced to N_2 for measurement) and water as they elute from the chromatographic column. The resulting gas is then ionized as in GC-MS and the masses of the combustion products are measured in a mass spectrometer specific to this application.

Because the components are separated in the gas phase, only compounds that can be volatilized can be separated using GC. High-temperature gas chromatography (HT-GC) may extend the range of compounds that can be separated, but it may also require conditions that are outside the capabilities of general-use gas chromatographs, while also definitely requiring a special high-temperature column. GC is generally limited in application to small molecules (less than 1,000 mass units) and those that are either readily vaporized in their native form (e.g., hydrocarbons) or that can be converted chemically into volatile forms. Fatty acids, such as those found in archaeological food residues, are not volatile due to strong hydrogen bonds between the terminal –OH groups within the carboxylic acid functional groups. A chemical conversion of the –OH to either an $-OCH_3$ (called a *methyl ester*) or $-OSi(CH_3)_3$ (called a *trimethylsilyl ester*) is necessary to render a fatty acid sufficiently volatile to be separated using gas chromatography. This conversion is called derivatization and occurs through the reactions shown in Figure 4. Nonvolatile components will not pass from the injection port to the GC column and thus will be neither separated nor detected in the analysis. For large biomolecules, a process called *pyrolysis* can be used in conjunction with GC; it is often abbreviated as Py-GC or Py-GC-MS depending on the detector used and involves the application of high temperatures in an inert environment to break large complex molecules into characteristic fragments. Derivatization and pyrolysis can be combined in a procedure sometimes termed *chemolysis*. This approach can eliminate the need for lengthy extractions, though it requires that a *pyrolysis unit* be installed at the GC injection port for work with solid samples.

Gas chromatography in archaeological applications

Gas chromatography (GC) – coupled to mass spectrometry (MS) as GC-MS – is arguably the most important analytical tool for investigating mixtures of organic molecules relevant in archaeology. Biomarkers, or molecular fossils derived from living organisms, have long been used in geology to understand the origins of petroleum. In archaeology, the biomarker idea has evolved to encompass molecules that provide evidence of past human activities as well. In geoarchaeology, gas chromatography provides a method for making connections between the organic composition of artifacts or sediments, past human activities, and the environment.



Gas Chromatography, Figure 4 Schematic of two derivatization reactions of palmitic acid ($C_{16:0}$): (**a**) methyl ester formation (methylation) and (**b**) trimethylsilyl ester formation (trimethylsilylation or silylation). *BSTFA + TMCS = N,O-Bis(trimethylsilyl) trifluoroacetamide + trimethylchlorosilane.

Peters et al. (2005) describe the analysis of a variety of different biomarkers and their use in understanding past human activity, including sourcing of Near East bitumens and the use of gums, resins, and pitch or tar derived from these resins as adhesives and their role in trade networks throughout the Old World. The most widespread application of gas chromatography in archaeology, though, is the analysis of lipids (Regert, 2011) preserved as residues in ceramic vessels and sherds. Evershed (2008) provides a critical review of organic residue analysis, as it is relevant to what he calls the Archaeological Biomarker Concept. Steele (2013) further describes some of the challenges in applying this biomarker concept in archaeological analysis, with cautionary notes on the importance of soil sampling and context for interpreting the results of such studies. Ceramic residue analyses are primarily undertaken using GC-MS. Further information can be made available from separations of the mixtures found within ceramic residues by use of stable isotope mass spectrometry, and even in some cases, direct radiocarbon dating on individual components of these mixtures.

There currently is great interest in archaeology to understand when, why, and how dairying practices first began to be implemented. Secondary animal products like dairy foods were thought to have followed the "neolithization" process, where hunting and gathering gave way to a reliance on farming of food crops after which these stable societies then proceeded to domestication of animals. GC-MS and GC-C-IRMS analyses of ceramics from across the Near East showed the first direct evidence of dairying dating back to the 7th millennium BC in parts of Anatolia, where cattle played a larger role in herding than did goats and sheep common in other areas (Evershed et al., 2008). The serial domestication of plants and then animals was not, however, universal. Dunne et al. (2012) describe residue analyses of ceramics excavated in Saharan Africa dating to the Middle Pastoral period (around 5200–3800 BC), which indicated a distribution of lipids characteristic of degraded animal fats and an isotopic signature consistent with that of dairy fats. This chemical analysis connects the excavated cattle bones with the use of secondary products from those herds at the distinct climatic period of the green Sahara without the previous domestication of plants. Recent studies have shown that this "neolithization" took place through different processes in Northern Europe, where subsistence through hunting and fishing rapidly gave way to dairy usage, as demonstrated by the isotopic and chemical characterization of ceramic residues (Cramp et al., 2014a). Even in the extreme north, above 60° latitude, where the challenges to farming would have been significant, evidence of the adoption of dairying has been observed in ceramics dating to around 2500 BC (Cramp et al., 2014b), which correlates closely with genetic studies indicating when lactase persistence became widespread in this part of the world. In order to digest milk sugar, lactose, the enzyme lactase must be continuously produced by the body into adulthood and not cease after nursing stops. Outram et al. (2009) used residue analysis in conjunction with faunal evidence to investigate the timing and process of the domestication of horses by the Botai people of Central Asia. While it was clear that horses were an important part of the Botai culture, a strong overlap between the isotopic compositions of horse milk fats and adipose fats representing meat have made it difficult to see clearly how mares' milk was utilized on its own (Outram et al., 2012).

GC and GC-MS characterization can be used to identify the geographic origin of bitumens based on the composition of *steranes*, steroid-like compounds, and terpanes. Connan (1999) reviews the use of GC-MS to determine the sources of bitumens used in building and other materials in the ancient Near East. Trade routes from sources to building sites were traced through Mesopotamia based on both sterane and terpane composition, as well as the carbon and hydrogen isotopic composition as determined by GC-C-IRMS. Analyses with GC and GC-MS were also used to show that bitumens used in embalming some Egyptian mummies likely originated from seeps located in the southern part of the Gulf of Suez (Barakat et al., 2005).

In addition to residues in or on artifacts, gas chromatography can be used to study the soils themselves, which may also contain biomarkers of human activity. Steroid compounds like coprostanol, a derivative of cholesterol formed in the gut of animals, can serve as biomarkers of fecal matter, and the spatial distribution of such compounds in soils can provide important information about the locations of ancient settlements. These compounds have low solubility in water and are stable in soils over long periods of time. While the mere presence of coprostanol in modern contexts can be used to indicate contamination from sewage, Bethell et al. (1994) found that relative abundances of several of the 5β-stanols, separated using GC and identified by MS, more reliably mark the presence of human feces in archaeological soils. GC-MS analysis of a variety of sterol compounds was used to reconstruct the history of the latrines in the Imperial Baths at Sagalassos, Turkey (Baeten et al., 2012). The change in sterol composition over time was indicative of a Byzantine-era use of the site for composting animal waste.

Analysis of lipids in archaeological soils can also provide a picture of site usage in the archaeological past. In the absence of reliable wood sources in Arctic regions, bone was one possible material that could have been used for cooking and heating. GC-MS lipid analysis of hearth soils at the Swan Point site in Alaska showed that animal bones likely served as fuel (Kedrowski et al., 2009). Unique archaeological features called "slab-lined pits" are found throughout Arctic Norway, but how these features functioned in the past was not well understood until lipid analysis of soils from the sites was undertaken (Heron et al., 2010). The fatty acid composition of the pit soils was consistent with their use in rendering marine mammal blubber for oil, though identification of specific mammals was not possible due to the variability observed in the composition of modern marine fats.

Summary

Gas chromatography is a valuable tool for the separation and characterization of organic molecules in a wide range of archaeological materials. It is commonly used in conjunction with mass spectrometry as GC-MS, which can, with the appropriate instrumentation, determine the stable isotope composition of individual components in a mixture. Analytically, gas chromatography is carried out in the gas phase, so the molecules under study must be either volatile or derivatized (as with lipids) to form volatile products.

Bibliography

Baeten, J., Marinova, E., De Laet, V., Degryse, P., De Vos, D., and Waelkens, M., 2012. Faecal biomarker and archaeobotanical analyses of sediments from a public latrine shed new light on ruralisation in Sagalassos, Turkey. *Journal of Archaeological Science*, **39**(4), 1143–1159.

Barakat, A. O., Mostafa, A., Qian, Y., Kim, M., and Kennicutt, M. C., II, 2005. Organic geochemistry indicates Gebel El Zeit, Gulf of Suez, is a source of bitumen used in some Egyptian mummies. *Geoarchaeology*, **20**(3), 211–228.

Bethell, P. H., Goad, L. J., Evershed, R. P., and Ottaway, J., 1994. The study of molecular markers of human activity: the use of coprostanol in the soil as an indicator of human fecal material. *Journal of Archaeological Science*, **21**(5), 619–632.

Connan, J., 1999. Use and trade of bitumen in antiquity and prehistory: molecular archaeology reveals secrets of past civilizations. *Philosophical Transactions of the Royal Society of London, Biological Sciences*, **354**(1379), 33–50.

Cramp, L. J. E., Evershed, R. P., Lavento, M., Halinen, P., Mannermaa, K., Oinonen, M., Kettunen, J., Perola, M., Onkamo, P., and Heyd, V., 2014a. Neolithic dairy farming at the extreme of agriculture in northern Europe. *Proceedings of the Royal Society B: Biological Sciences*, **281**(1791), 20140819.

Cramp, L. J. E., Jones, J., Sheridan, A., Smyth, J., Whelton, H., Mulville, J., Sharples, N., and Evershed, R. P., 2014b. Immediate replacement of fishing with dairying by the earliest farmers of the northeast Atlantic archipelagos. *Proceedings of the Royal Society B: Biological Sciences*, **281**(1780), 20132372.

Dunne, J., Evershed, R. P., Salque, M., Cramp, L., Bruni, S., Ryan, K., Biagetti, S., and di Lernia, S., 2012. First dairying in green Saharan Africa in the fifth millennium BC. *Nature*, **486**(7403), 390–394.

Evershed, R. P., 2008. Organic residue analysis in archaeology: the archaeological biomarker revolution. *Archaeometry*, **50**(6), 895–924.

Evershed, R. P., Payne, S., Sherratt, A. G., Copley, M. S., Coolidge, J., Urem-Kotsu, D., Kotsakis, K., Özdoğan, M., Özdoğan, A. E., Nieuwenhuyse, O., Akkermans, P. M. M. G., Bailey, D., Andeescu, R.-R., Campbell, S., Farid, S., Hodder, I., Yalman, N., Özbaşaran, M., Bıçakcı, E., Garfinkel, Y., Levy, T., and Burton, M. M., 2008. Earliest date for milk use in the Near East and Southeastern Europe linked to cattle herding. *Nature*, **455**(7212), 528–531.

Heron, C., Nilsen, G., Stern, B., Craig, O., and Nordby, C., 2010. Application of lipid biomarker analysis to evaluate the function of 'slab-lined pits' in Arctic Norway. *Journal of Archaeological Science*, **37**(9), 2188–2197.

Kedrowski, B. L., Crass, B. A., Behm, J. A., Luetke, J. C., Nichols, A. L., Moreck, A. M., and Holmes, C. E., 2009. GC/MS analysis of fatty acids from ancient hearth residues at the Swan Point archaeological site. *Archaeometry*, **51**(1), 110–122.

Outram, A. K., Stear, N. A., Bendrey, R., Olsen, S., Kasparov, A., Zaibert, V., Thorpe, N., and Evershed, R. P., 2009. The earliest horse harnessing and milking. *Science*, **323**(5919), 1332–1335.

Outram, A. K., Kasparov, A., Stear, N. A., Varfolomeev, V., Usmanova, E., and Evershed, R. P., 2012. Patterns of pastoralism in later Bronze Age Kazakhstan: new evidence from faunal and lipid residue analyses. *Journal of Archaeological Science*, **39**(7), 2424–2435.

Peters, K. E., Walters, C. C., and Moldowan, J. M., 2005. *The Biomarker Guide. 1. Biomarkers and Isotopes in the Environment and Human History.* Cambridge: Cambridge University Press.

Regert, M., 2011. Analytical strategies for discriminating archeological fatty substances from animal origin. *Mass Spectrometry Reviews*, **30**(2), 177–220.

Steele, V., 2013. Organic residues in archaeology: the highs and lows of recent research. In Armitage, R. A., and Burton, J. H. (eds.), *Archaeological Chemistry VIII*. Washington, DC: American Chemical Society. ACS Symposium Series 1147, pp. 89–108.

Cross-references

Organic Residues
Privies and Latrines

GEOARCHAEOLOGY, HISTORY

Christopher L. Hill
Graduate College, Boise State University, Boise, ID, USA

Introduction

Since the 1970s, the term "geoarchaeology" has been applied to research that uses geoscience techniques to examine and evaluate the archaeological record. Historically, the use of the geosciences to examine archaeological questions began much earlier in the 1700s and 1800s, and by the middle of the nineteenth century, earth scientists had started systematically and empirically to study the relationships between humans and the environment by using geoscience methods to interpret the archaeological record. The history of geoarchaeology includes not only the application of earth-science methods to archaeology but also the study of long-term patterns in the interactions between people and natural systems (Hill, 2005). These methods align geoarchaeology with environmental archaeology and Quaternary geology, and they connect it to approaches used in physical geography and geomorphology, historical ecology, and landscape archaeology. Thus, geoarchaeology is fundamentally an ecological science that studies the relationships between humans and the earth.

From the time they were first applied, earth-science methods have been used to examine the archaeological record at a variety of spatial and temporal scales. They have been employed in the study of raw materials, artifacts, sediments, post-burial changes at sites, landforms, and landscape settings, as well as the dating of archaeological contexts. Besides the use of earth-science techniques, a major theme in the history of geoarchaeology has been the examination of long-term linkages between human populations and other components of the geosphere and biosphere, including questions connected with human origins, biological and behavioral evolution, and human response to (and impact on) environments.

The geosciences and archaeology prior to 1900: time and context

The application of stratigraphy to interpret archaeological sites builds on the principles formulated by Niels Stensen, also known as Nicolas Steno, in 1669 and James Hutton in 1788. Stensen's work provided the basis for the principles of superposition and original horizontality so crucial to the study of Quaternary strata, while Hutton's "Theory of the Earth" formulated a view of time that would lead to conclusions regarding the antiquity of humans by the 1850s. Early recognition of the value of understanding the context of artifacts is reflected in John Frere's 1797 report of the discovery of stone hand axes (Frere, 1800) within a stratified sedimentary sequence in England (Rapp and Hill, 2006). Describing the location of the artifacts and the sequence of sediments, he delineated the bedding and density of artifacts in the deposits and discussed the implications of his observations. The emergence of ecological perspectives connected with past human-environment interactions is visible in the pioneering works of Alexander von Humboldt and Charles Lyell. Humboldt's first formal fieldwork in geology and archaeology was in 1789 in the Rhine Valley. Then from 1799 to 1803, he conducted field studies of archaeological features in South America and Mesoamerica. His observations were often in the realm of historical ecology and landscape archaeology, characterized by an empirical approach. Humboldt provided descriptions of the raw materials used in the archaeological monuments (e.g., basalt for statues, clay, and mixed stone in the temples). In one instance, where a road cut exposed the internal structure of the pyramid of Cholula, he described its distinct layers of sundried brick and clay (Humboldt, 1814, 105). Humboldt also showed an interest in landscape evolution and human activities. In 1800, he studied the changes of lake levels in Venezuela and attributed the changes to a combination of climate change and human activities such as deforestation, cultivation, and clearing of the plains.

The publication of the three volumes of *Principles of Geology* by Charles Lyell in 1830–1833 emphasized the value of uniformitarian theory: using observations of ongoing natural processes to understand the past. The first and second volumes included descriptions of the geologic context of the archaeology of Vesuvius (Pompeii and Herculaneum), caves, and shipwrecks. Lyell provided summaries of archaeological and paleontological sites, such as those studied by William Buckland at Paviland Cave (Goat's Hole) and cave sites in France containing bones and artifacts. A concern for site formational processes and context is reflected in Lyell's evaluations: "Must we infer that man and these extinct quadrupeds were contemporaneous…? We should unquestionably have arrived at this conclusion if the bones had been found in an undisturbed *stratified* deposit…." (1831, 225).

This influential work also recognized the contribution of human activity to environmental change. Lyell used Iron Age Roman roads covered with several meters (8 ft) of peat to document changes to the landscape (Lyell, 1831, 213), and he commented on the transformation of the landscape by deforestation since it was described by Caesar.

During the 1830s, Boucher de Perthes applied the stratigraphic approach to document the context of stone artifacts and bones of extinct animals in ancient river deposits along the Somme Valley, in France. His studies, begun in 1837, were continued by Marcel Jerome Rigollot and included stratigraphic profiles showing artifacts in association with the remains of extinct animals. Their observations were not considered conclusive; it was not until the middle of the nineteenth century that a consensus was reached on the question of human antiquity.

A prominent example of the application of geologic methods in North America during this early period is Lyell's observations on human remains and their association with deposits containing the fossils of extinct animals in Mississippi. Lyell's field studies in 1846 led him to conclude that the association was probably a product of redeposition or mixing. In 1848, Ephraim Squier and Edwin Davis published *Ancient Monuments of the Mississippi Valley*, which provides a valuable example of how American archaeologists were implicitly using geologic principles by this time. Stratigraphic methods were used to determine whether human or other natural processes had created mounds found in the Mississippi Valley. Their research demonstrated that attention to the geologic context of artifacts, the same general approach applied by Boucher de Perthes and Rigollot in France, was also being used in North America.

The Antiquities of Wisconsin, written by Increase Lapham (1855), is an important early example of how the archaeological record could be used to document the connections between human land use and landscape change. Based on counting rings from trees growing on quarry rubble, he demonstrated that ancient copper mines were at least 300 years old. He also used the archaeological record to determine the antiquity of the historic forests. Lapham demonstrated that prehistoric mounds were formed by the gradual addition of materials by humans in the planting of corn, and he documented fields of up to 300 acres that were the remnants of ancient garden beds. Lapham inferred that this evidence indicated 3,000 years of landscape evolution related to the switch from hunting and gathering to agriculture, followed by the construction of mounds, then garden beds, and eventually the restoration of the forest prior to the start of European settlement. Thus, large tracts of land covered by forest in historic times had previously been cultivated landscapes, suggesting "no very great antiquity can be assigned to the dense forests of Wisconsin" (Lapham, 1855, 91).

Collaboration between archaeologists and geologists in Europe during the middle of the nineteenth century resulted in a much clearer understanding of the sequential development of societies and human antiquity. Johan Forchammer, a professor of geology at the University of Copenhagen, collaborated with archaeologist Jens Worsaae in the study of shell middens in Denmark and Sweden. In 1848, they first undertook multidisciplinary field studies with the Danish paleontologist Japetus Steenstrup, eventually demonstrating that the mounds were human habitation sites and providing some of the basis for the refinement and subdivision of the three-age system.

The history of events leading to the acceptance of prehistoric people and other animals existing together during the Ice Age is a very important example of the early use of earth-science techniques to study the human past. It was after the 1858 excavations of Brixham Cave in England, directly supervised by William Pengelly, that the evidence for the presence of humans during the Ice Age was accepted. This conclusion was based on the finds from caves in Britain and reevaluations of the alluvial deposits in France. The Brixham Cave discoveries were convincing partly because of the systematic excavation techniques devised by Pengelly to document the contextual relations between the objects recovered during the excavations and also because fossils of animals such as *Elephas* (*Mammuthus*) and *Rhinoceros* were found in the same strata as stone artifacts, which were all covered by a stalagmite-limestone floor. Besides the actual spatial relationships of artifacts and fossils within the sealed cave sediments, the confidence in the manner of the excavations and close interaction between Pengelly and Hugh Falconer, Joseph Prestwich, and Charles Lyell led to the consensus.

Falconer's initiative led to the careful excavations at Brixham Cave. In 1858, his own field observations convinced him how important it would be to travel to the Somme Valley to reevaluate the discoveries in the French alluvial gravels reported by Boucher de Perthes. The next year, Prestwich and John Evans followed; they traveled first to Abbeville and later to Saint Acheul. At Saint Acheul, they viewed stone artifacts embedded in sediments that also contained the remains of extinct animals. Lyell also visited the French discoveries at Abbeville in July 1859, concluding that the stone tools dated to the same time as the mammoth fossils. These events led to a series of public announcements at scientific meetings in Great Britain. Although Lyell was not the primary researcher, his credibility enabled him to validate the evidence from Abbeville and Brixham Cave at the 1859 meeting of the British Association for the Advancement of Science. Prestwich's observations were published the following year in the *Proceedings* of the Royal Society of London. Thus, geoscience techniques and concepts were crucial to validating the association of stone artifacts with the remains of extinct animals and the conclusion that humans had been part of the Ice Age world.

During the 1860s, a wave of influential publications evaluated the geologic contexts of archaeological discoveries or examined the impact of human activities on the environment. Lyell's *Geological Evidences of the Antiquity of Man* was first published in 1863. The book contained a detailed review of the geologic setting of Pleistocene and Holocene archaeological discoveries and glaciation, and it also included several chapters on evolution (Darwin's *Origins* had been published in 1859). John Lubbock's *Pre-Historic Times* (1865) captured the nature of investigations at the time: "Nor does there appear to be any reason why those methods of examination which have proved so successful in geology, should not also be used to throw light on the history of man.... Archaeology forms, in fact, the link between geology and history" (1865, 2–3). In 1864, the first edition of *Man and Nature* by George Perkins Marsh documented the extent of long-term changes to the environment produced by human action. Although in a discussion of ancient climates, he alludes to the Swiss lake dwellings, the Danish shell middens, and other examples from prehistoric archaeology, Marsh concentrated on ancient examples of landscape change caused by irrigation, water diversion, drainage, agriculture, and mining.

Classical archaeology also utilized geoscience methods during the second half of the nineteenth century, especially in the application of stratigraphic principles in the refinement of excavation techniques. Giuseppe Fiorelli's excavations at Pompeii, starting in 1860, emphasized stratigraphic control as did the later excavations at Samothrace by Alexander Conze in 1873 and at Olympia by Ernst Curtius in 1875. At Hissarlik (Troy), starting in 1871, Heinrich Schliemann became the first to excavate a multilayered tell, although more careful stratigraphic excavations were conducted there by Wilhelm Dörpfeld in 1882.

Along with this continued concern for improving the reliability and usefulness of field observations, broader themes were developed concerning humans and changing environments. In the 1874 edition of *The Earth as Modified by Human Action*, Marsh referred to the proposal by the Italian geologist Antonio Stoppani (1873) that a new geologic period should be designated the "anthropozoic" because the existence of humans resulted in a great impact on the earth, an idea revived with the proposal of the term "anthropocene" in the early twenty-first century (Crutzen, 2002; Zalasiewics et al., 2008). James Geikie's *The Great Ice Age and its Relation to the Antiquity of Man*, first published in 1874, provided a systematic account of what was then known regarding climate and the geologic context of deposits associated with Paleolithic artifacts, arguing for interglacials in Europe. The third edition, published in 1894, added a section on North America by T. C. Chamberlin, which summarized the evidence for multiple glaciations but, ironically, did not explicitly connect the geology to the archaeology.

The close relationship between geography, geology, anthropology, and archaeology is also reflected in the establishment of both the United States Geological Survey (USGS) and the Bureau of American Ethnology (BAE) in 1879 through the efforts of John Wesley Powell. He was director of the BAE until 1902 and served as second director of the USGS from 1881 to 1884. His *Report on the Lands of the Arid Regions of the United States* is an ecological, conservation-based approach to landscape dynamics and land use. Other geologists played a prominent role in the early development of the Smithsonian's BAE. For example, geologist William Henry Holmes succeeded Powell as director. After the studies conducted by Squier and Davis earlier in the 1840s, Cyrus Thomas used stratigraphic principles in the 1880s to study the archaeological mounds in the Mississippi Valley, as did William Henry Holmes and Frederick W. Putnam with their investigations into the possibility of an "American Paleolithic." Putnam in particular was known for careful archaeological excavations that employed arbitrary levels and documentation of stratigraphy by the early 1880s.

The key to the early man controversy in North America lay in the delineation of a relative sequence of glacial-age deposits for the continent – one of the goals of USGS geologists in the 1880s. For Powell (1890), evidence for a version of the Paleolithic in North America had to be based on geology. Likewise, Holmes, an energetic critic of the American Paleolithic, wrote that the only reliable test for human antiquity in North America rested on geologic evidence. He also did significant work in excavating ancient mines and quarries. During the last decade of the nineteenth century, a range of researchers including Henry W. Haynes, Charles Abbott, and Rollin D. Salisbury believed the reliability of the geologic context of potential Paleolithic artifacts to be very important. The application of geologic methods to buttress the argument that humans existed in North America during the Ice Age is reflected in Holmes's 1893 *Journal of Geology* and *American Geologist* articles concerning contextual problems associated with potential Paleolithic sites in Ohio and Minnesota. Newton Horace Winchell summarized many of the questions about the geologic context of early humans in North America in his presidential address to the Geological Society of America (GSA) in 1902.

1900–1950: collaboration, techniques, and a legacy provided

The first part of the twentieth century witnessed a variety of interactions between archaeology and the geosciences. Multidisciplinary cooperation characterized some of the research during the period. There were instances when geologists, geographers, and paleontologists coordinated their efforts with archaeologists working in the same area. These efforts resulted in regional studies that could be used as the basis for paleoclimatic interpretations and the development of a time framework that could also be applied to dating archaeological sites. Geomorphic, stratigraphic, and paleontologic criteria were critical to the chronological studies. After 1900, more laboratory specialists were involved in the analysis of specimens collected as part of archaeological research. Investigations of landscapes incorporated the study of both natural processes and human activities, and a growing list of examples of sedimentologic and stratigraphic applications to the evaluation and interpretation of archaeological sites emerged. The pattern of collaboration and application of techniques and approaches from geology and geography during the first half of the twentieth century developed a lasting legacy that later led to the formal establishment of the discipline of geoarchaeology.

New techniques from the geosciences were applied to questions linked to understanding the dynamics of landscapes connected with archaeological sites. The pollen-analysis methods developed by Lennart von Post were first applied in Scandinavia between 1908 and 1916, revealing climate intervals associated with postglacial environmental change. The technique of varve dating was first applied by Gerard J. De Geer in 1905 in Sweden and later by Matti Sauramo in Finland and by Ernst Antevs in North America. Tree rings were employed to provide archaeological chronologies by Andrew E. Douglass after 1914. Remote sensing techniques were applied during the early twentieth century in the form of aerial photography. In 1906, aerial photographs of Stonehenge revealed buried features not visible from the surface. Later, in the 1920s, a major effort to use aerial photography to discern archaeological features was conducted in England. O. G. S. Crawford (1923) realized the potential of using aerial photography to place archaeological sites within the context of broader landscapes. Using this remote sensing method, he was able to map the location of over 200 archaeological sites in southern Britain (Crawford and Keiller, 1928) and combine the study of archaeological settlement patterns with ancient landscapes. Charles Lindbergh applied the technique of aerial photography in the study of the archaeological ruins and their landscape context in the American Southwest in collaboration with Alfred V. Kidder.

The relationships of environmental and climatic change to human adaptation were among archaeology's principal concerns after 1900 and provided opportunities for multidisciplinary cooperation between geologists, geographers, and archaeologists. Raphael Pumpelly, who was elected President of the GSA in 1905, applied the rules of geologic reasoning to archaeology in his expeditions to Turkestan. These studies examined the origins and growth of the Anau civilization and also investigated the influence of environmental change in central Asia. During the first field season of 1903, Pumpelly conducted a reconnaissance survey documenting the distribution and environment of archaeological sites, while William Morris Davis and Ellsworth Huntington studied the geomorphic evidence for a series of glacial-interglacial episodes that documented climate and environmental change in the region during the Quaternary. During the 1904 season, Pumpelly pursued landscape studies. Huntington assisted Hubert Schmidt – who had trained under Dörpfeld in the excavation of Troy – with systematic archaeological excavations. Results of the expedition, *Explorations in Turkestan*, were published as two volumes in 1905 and 1908, and Pumpelly presented a summary of the field results entitled "Interdependent evolution of oases and civilizations" at the 1906 meeting of the GSA.

Interpretations of the archaeological record at the site-specific scale relied on a growing awareness of the value of stratigraphic control. Max Uhle (1903) used the phrase "geological stratification" to describe the context of archaeological discoveries in Peru. Later, while excavating a shell mound on the east shore of San Francisco Bay, Uhle (1907) documented a sequence containing artifacts in ten strata overlying alluvial clay. Influenced by the approaches observed in Europe, Manuel Gamio and Nels C. Nelson employed stratigraphic principles at other American sites, and A. V. Kidder, in turn, applied the techniques of stratigraphic excavation to the ruins at Pecos, New Mexico.

In 1911, Gamio initiated stratigraphic excavations at Azcapotzalco in Mexico City, Mexico. Excavations revealed three groups of pottery and their stratigraphic relationships, which were used by Gamio to demonstrate the relative order of the artifacts. In 1914, after observing the methods of stratigraphic excavation by Hugo Obermaier and Henri Breuil at Castillo Cave, Nelson employed similar methods at Pueblo San Cristobal. Kidder's excavations at Pecos Pueblo also applied a stratigraphic methodology to evaluate the relative age of archaeological materials. Beginning in 1915, Kidder's excavation techniques enabled the collection of artifacts from distinct deposits instead of the arbitrary levels used by Nelson and Gamio (Kidder, 1924). This made it possible to document the relative stratigraphic position of pottery types within the archaeological deposits and allowed him to demonstrate that specific pottery types occurred in particular strata; it also enabled him to document the presence of a sequence and relative ordering of these types. Other research in the American Southwest soon followed. Kirk Bryan began geologic studies of Chaco Canyon in 1924 (Bryan, 1954), and dendrochronology was used by A. E. Douglass (1929) to date the sequence of changing artifact types at Pecos and at other sites. The extension and elaboration of the techniques of stratigraphic excavation after World War I are exemplified by the innovations of Mortimer Wheeler, first at Iron Age sites in Britain and later in the at Harappan sites in the Indus Valley (Wheeler, 1954).

After participating in Pumpelly's 1903–1904 Turkestan explorations, Ellsworth Huntington pursued the idea that the physical environment in the form of climate change was a primary factor in determining the development of human societies. Notable examples of his research include *Civilization and Climate* (1915, first edition; 1924, third edition) and "Maya civilization and climatic changes" (1917).

The concern with validation of potential Ice Age artifacts continued to be of interest in North American research in the early twentieth century. As before, purported Pleistocene human remains or artifacts had to be verified by unquestionable stratigraphic evidence. Interactions among American archaeologists and geologists during this period are exemplified by articles published in 1917 in the *Journal of Geology*. Discussions revolved around the sedimentologic context and validity of association for artifacts and fossils found at Vero, Florida. Rollin Chamberlin and George MacCurdy concluded that the fossils were in secondary deposits, but Chamberlin also believed that there was evidence to support the association between the extinct fauna and the human remains. In contrast, Aleš Hrdlička believed the discovery could not be supported because of the depositional context of the remains.

The field studies of Elinor Wight Gardner illustrate the collaboration between geologists, paleontologists, and archaeologists in the 1920s and 1930s. In 1925–1926 and 1928–1929, Gardner collaborated with archaeologist Gertrude Caton-Thompson in the study of the northern Fayum, southwest of Cairo, Egypt. Gardner focused on mapping the region, tracing the shorelines of an ancient lake associated with Neolithic archaeological sites. This work was published in the *Geographical Journal* in 1929 and later as a two-volume monograph (Caton-Thompson and Gardner, 1934). In 1930–1931 Gardner and Caton-Thompson began a study of Kharga Oasis in the Egyptian Western Desert, which included an aerial reconnaissance. Gardner continued the fieldwork without Caton-Thompson in 1932–1933. With Dorothy Garrod, she conducted field studies during 1935 along the eastern coast of the Mediterranean in the vicinity of Haifa. They studied a kurkar-hamra (sand-red silt) sequence containing Middle Paleolithic artifacts that could be related to the nearby excavations at et-Tabun and el-Wad, Mount Carmel. Later that same year, they explored the northern Jordan Valley and found Acheulian artifacts in association with fauna at Gesher Benot Ya'akov (Jisr BanatYaqub). In 1937, Gardner collaborated with Dorothea Bate in the excavation of Pleistocene deposits at Bethlehem. Gardner also conducted geomorphic studies as part of an expedition to the Arabian Peninsula in 1937–1938, excavating and mapping parts of Hureidha, in the Hadhramaut, Yemen.

This period saw a growing emphasis on the application of geographic concepts to interpreting the landscape settings and patterns of archaeological sites. For example, Cyril Fox (1923, 1932) examined the distribution of archaeological sites within the context of vegetational patterns and environmental settings. In a review of the relationship between nature and prehistoric humans, Clark Wissler (1924, 312) stated "the anthropologist is… not only trying to show what all forms and forces of nature have done to man, but even with more emphasis what man has done to nature." His statement was a deliberate attempt to apply ecological concepts of resource use to patterns of human behavior.

Carl Sauer articulated a view of the landscape as a product of space, time, and natural and human processes. Sauer conceptualized landscape as the combination of physical geology and modification by humans or the natural landscape as transformed by humans (Sauer, 1925). He designated the study of archaeological sites in relation to their environmental setting as "archaeogeography" (Sauer and Brand, 1932, 2). This approach is illustrated by the studies Sauer and Brand conducted, partly in collaboration with Alfred Kroeber, which examined the distribution, size, and relationship of archaeological sites. Sauer's approach was to look at archaeology at the landscape scale: "I considered that archaeologists were too concerned with the taxonomy of artifacts and not enough with the analysis of habitat and habitation" (Sauer, 1939 in West, 1979).

The nature of the interaction between archaeology and geology throughout the world during the early part of the twentieth century is represented in the volume *Early Man* (MacCurdy, 1937). Studies linking the geosciences and archaeology in Eurasia included reviews by Dorothy Garrod on the Near East, Teilhard de Chardin on the stratigraphy of China, Helmut de Terra on India, and Gerard De Geer on geochronology, to name a few. Examples focused on North America included geomorphologist Morris Leighton's essay on the significance of profiles of weathering in stratigraphic archaeology, paleobotanist Paul Sears's paper on the use of pollen for dating archaeological deposits, geologist Ernst Antevs's essay on climate and "early man," and geologist Kirk Bryan's discussion of the geology of Folsom deposits (the discoveries at Folsom in 1927 had documented the primary association between undisputed artifacts and extinct fauna, demonstrating Ice Age human antiquity in the New World). The volume demonstrates that many approaches derived from the natural sciences were being applied in early twentieth-century prehistoric studies.

Evidence of multidisciplinary interaction in the Old World is reflected by Frederick Zeuner's application of archaeology for its geochronological and climatic implications. Zeuner was Professor of Environmental Archaeology at the University of London's Institute of Archaeology. *The Pleistocene Period* (Zeuner, 1945) reviewed the principles of stratigraphy, including soils and terraces, and then summarized the chronology of climate change and its impact on patterns of biogeography. *Dating the Past* (Zeuner, 1946, first edition; 1952, third edition) reviewed chronologic approaches to dating archaeological sites and constructed regional chronologies (just at the time radiocarbon dating was first being used). Thus, the third edition provided a chronologic framework for archaeological discoveries that relied on stratigraphic and geomorphic evidence, combining this data with the first sets of radiocarbon dates from the laboratories at Chicago and Lamont Geological Observatory of Columbia.

In North America, a pervasive geoscience approach is connected with archaeological research in the Great Plains and Southwest (Haynes, 1990; Holliday, 1997; Mandel, 2000b). Edgar Howard's research in the American Southwest used geologic and archaeological evidence, including excavations of caves and the study of lake sediments in New Mexico. In 1935, he proposed a reconstruction of the Late Pleistocene environments on the southern High Plains and reviewed the chronological and climatic theories associated with the end of the Pleistocene. Ernst Antevs (1935) studied the geologic and archaeological aspects of the Clovis type site at Blackwater Draw, New Mexico, as a member of Howard's expedition in 1934. His series of influential publications from the 1930s through the 1950s employed geologic techniques to develop paleoclimatic models that could be related to archaeological studies.

In the 1920s, Kirk Bryan investigated evidence for environmental change at Chaco Canyon, New Mexico. From about 1924 to 1950, Bryan dominated research at the interface between geology and archaeology in North America. Although a major facet of Bryan's research was the application of paleoclimatic chronologies to date Paleoindian sites, he also made efforts to delineate the environmental settings and interpretations of other archaeological sites. The interpretations of the settings were largely based on evaluations of the processes of landscape evolution linked to erosion and sedimentary deposition that could be affected by climatic processes and human activity (cf. Bryan, 1925).

Bryan's legacy is also reflected in his collaborative studies where he often served as teacher and mentor. Bryan initiated geologic studies on the Lindenmeier bison site in Colorado in 1935, returning with Louis Ray in 1936. Ray conducted field studies from 1936 to 1938 (Bryan and Ray, 1940). In 1937 and 1938, Bryan's former student Harold T. U. Smith studied the alluvial terrace deposits in Kansas as part of a multidisciplinary archaeological study with Loren Eiseley. In 1938, Bryan collaborated with Claude Albritton, Jr. and archaeologists J. C. Kelley and T. N. Campbell to investigate the Quaternary geology of the Davis Mountains (Albritton and Bryan, 1939). Sheldon Judson carried out a geologic study of the San Jon site and its Plainview artifacts in northeastern New Mexico under Bryan's supervision (Judson, 1953). Bryan and Roberts visited the site in 1940, and Judson and Bryan conducted a reconnaissance in 1941 with fieldwork completed in 1947 by Judson. In 1941, Emil Haury excavated the deep sequence at Ventana Cave in Arizona, with Bryan studying the stratigraphy in 1942.

In 1947, Bryan's student Herbert E. Wright, Jr. conducted a sedimentary and geomorphological study of the rock-shelter at Ksar Akil, near Beirut, Lebanon, which contained Mousterian and Upper Paleolithic archaeology. Wright then participated as the geologist with Robert Braidwood's multidisciplinary Jarmo project in Kurdistan, northern Iraq. Braidwood's interdisciplinary project ran from 1947 to 1955. In 1948, Bryan initiated the investigations of the rock-shelter at La Colombière in the Rhone Valley of southeastern France, later completed by Judson. Investigations at the Horner site, located near Cody, Wyoming, were started in 1948 with Loren Eiseley and Glenn Jepsen. In 1950, Bryan visited Fred Wendorf's field camp at the Petrified Forest in Arizona. Shortly after, while in the field at the Horner site in 1950, Bryan died. By the middle of the 1900s, Bryan and his collaborators had effectively applied a geoscience approach to archaeological questions. Some of Bryan's students continued active research into the early part of the twenty-first century, directly training and less directly influencing several generations of Quaternary scientists.

1950s to today: bridging applications, geoarchaeology defined and organized

During the 1950s and 1960s, many people who would become the founding group of the new "geoarchaeology" were beginning their careers. They actively pursued research that would later be labeled as geoarchaeology or archaeological geology starting in the 1970s and 1980s. Much of this research was conducted by specialists on multidisciplinary teams, applying standard geoscience field techniques while taking advantage of advances in analytical techniques. Innovations in dating, such as the development of radiocarbon dating in the 1940s by Willard Libby (Arnold and Libby, 1949) or the application of K-Ar dating to late Cenozoic stratigraphic sequences in the 1960s, reinforced the value of close interaction between geoscientists and archaeologists. However, the development of a recognized discipline was derived from collaborative field studies and from an expanding network of practitioners focused on applying earth-science methods and concepts to understanding ecological patterns of the human past.

Research at the interface of the geosciences and archaeology thrived during the 1950s. In the American Southwest and Great Plains, environmental studies of the Late Pleistocene prevailed. Glen Evans conducted stratigraphic studies at the Clovis type site in 1949 and 1950 while continuing studies he had started at Lubbock Lake, Texas. Judson, John Schullinger, and John Moss continued the geological studies that had been started at the Horner site. Moss later conducted detailed studies of the nearby Pleistocene terraces. In 1951, Emil Haury and Ernst Antevs began investigations in Greenbrush Draw, Arizona, where Haury excavated the Naco mammoth Clovis site in 1952. This was followed by studies of the nearby Lehner mammoth Clovis site in 1955–1956. In 1954, Harold Malde conducted geologic investigations of the Dent mammoth Clovis site and the Cody complex Claypool site in Colorado. At about the same time, Luna Leopold and John Miller were studying the postglacial alluvial valleys of Wyoming. In 1953 and 1954, Fred Wendorf, in collaboration with Alex Krieger and Claude Albritton, undertook field studies of the Late Pleistocene Midland site in west Texas. In 1956, Wendorf and Miller conducted field studies of the relationships between alluvial terraces and Pueblo sites in New Mexico. That same year, Wendorf and A. E. Dittert excavated at the Clovis type site, to which Wendorf returned in 1958 as part of the High Plains Ecology Project. C. Vance Haynes, Jr. began his geological studies of archaeological sites in the 1950s, sometimes working in collaboration with archaeologist George Agogino. For example, Haynes and Agogino investigated the Hell Gap site in Wyoming in 1959 and 1960. Charcoal collected by Haynes at the Lindenmeier bison kill led to the first reliable radiocarbon date from a Folsom site (Haynes and Agogino, 1960). Likewise, in Old World studies, Sheldon Judson conducted a study of the geological and geographical setting of Abri Pataud in the Dordogne region of France in 1957, 1958, and 1968. The study did not focus on the site stratigraphy but rather attempted to relate the sediments and geomorphic features in the Vézère River valley to the site. Concurrent fieldwork by John Stewart documented the regional glacial geology (Judson, 1975). John Miller began sedimentological studies of the stratigraphy within Abri Pataud in 1958; these were later completed by Bill Farrand in 1964. The primary purpose for field investigations in Egypt by Karl Butzer during 1956 and 1958 was to study Pleistocene stratigraphy. The 1958 studies included topographic survey and mapping of surficial deposits, in cooperation with Werner Kaiser, related to Neolithic and Predynastic sites in the Nile Valley.

The benefits of interactive collaboration between geologists and archaeologists are indicated by the publication of a series of works by the end of the 1950s. Mortimer Wheeler wrote: "Archaeology is increasingly dependent on a multitude of sciences and is itself increasingly adopting the methodology of a natural science. It draws today upon physics, chemistry, geology, [and] biology...." (Wheeler, 1954, 2). Hallam Movius, Jr. (1949, 1957) stressed the bond between prehistoric archaeology and the natural sciences. The goal of investigating human adaptation to natural environments, Movius emphasized, could be achieved through natural-science studies concerned with the sequence and correlation of Pleistocene events. He argued that environmental reconstruction was important. Troy Péwé's paper in *American Antiquity* (1954) emphasized the geologic approach to dating archaeological sites and focused on the value of understanding the geologic and biotic responses to climate changes to help evaluate archaeological contexts. In a volume published by the US National Academy of Sciences and the National Research Council, Wright emphasized that the most useful contributions geologists could make to archaeological problems were in the interpretation of the physical and climatic environment. He noted the importance of this approach to the study and evaluation of the whole archaeological site and suggested that Pleistocene geologists would be most interested in the climatic environment and chronology associated with archaeological sites. In the same volume, Judson wrote about the value of collaboration between Pleistocene geologists and archaeologists, and Braidwood wrote that some might choose to be "natural-science archaeologists" and described a "Pleistocene ecology" or "Quaternary geography" which would "include man as an element in and a factor acting upon the environmental scene" (Braidwood, 1957, 15–16).

Ian Cornwall's *Soils for the Archaeologist* (1958) demonstrated the great potential sediments and soils offered in archaeological analysis and interpretation. It has been described as the first systematic attempt at geoarchaeology (Butzer, 1982). Cornwall argued for contextual studies in archaeology that used the geosciences. Soon afterward, Edward Pyddoke published *Stratification for the Archaeologist* (1961). He advocated that, besides interpreting and understanding human activities, the job of the archaeologist was also to evaluate the stratigraphic context of artifacts. The books by Cornwall, Pyddoke, Wheeler, and Zeuner show that the basis for an earth-science approach was present in the study of Old World archaeology by the 1960s. This is reflected in the studies of environment and human ecology in Egypt conducted by Butzer and his advocacy of the use of the methods of Quaternary geology, geography, and geomorphology to study the immediate site and its wider habitat or setting (Butzer, 1959a; Butzer, 1959b; Butzer, 1960). The role of geology in Pleistocene paleoecology and archaeology was summarized by Haynes (1964a), providing his views on the importance of geologic stratigraphy, interdisciplinary cooperation, and the geologist's role in paleoecologic interpretations.

Karl Butzer's landmark text *Environment and Archaeology* (1964) used the phrase "Pleistocene geography," which was chosen because it served to "emphasize both man and environment" during the Quaternary (Butzer, 1964, 4). Butzer first published his detailed studies and reviews of the stratigraphy and climatic chronology of the late Quaternary in the Near East in the 1950s. Following those publications, Butzer's *Environment and Archaeology* provided a worldwide comparison of archaeological and environmental contexts, placing an emphasis on the value of integration. It included sections on stratigraphy and chronology; vegetation, soils, and geomorphology as environmental indices; mammal biogeography; sediments; regional reconstructions; and human-land relationships. Starting in the 1950s and throughout the 1960s, Butzer applied this approach to his fieldwork in Egypt, East Africa, and Spain. Working primarily along the Nile Valley, he focused on the late Quaternary of Upper and Middle Egypt and then expanded southward into Nubia as part of the Yale studies in 1962–1963. In 1961–1963, and 1967, he conducted research associated with the excavations of Torralba-Ambrona in Spain, and, in 1969, he participated in an expedition to Omo in southwestern Ethiopia.

Other important studies combining geology and archaeology were initiated in the Nile Valley and East Africa during this time. In the Nile Valley, Rhodes Fairbridge and Ralph Solecki conducted studies in 1961–1962 along the Nile in Sudan, followed by four seasons of fieldwork by Jean de Heinzelin (beginning in 1961, then as part of the Combined Prehistoric

Expedition, or CPE, from 1962 to 1965). Geological fieldwork by Butzer and Carl Hansen (1962–1963) and Robert Giegengack (1963–1967) in Egypt and Nubia were part of Yale University's expeditions. In Nubia, Claude Albritton conducted field studies of the Tushka area during the 1965–1966 field season as part of the CPE. In East Africa in 1962, Richard Hay initiated his geologic studies of Olduvai Gorge (Hay, 1963). This was the beginning of a long-term study that would produce *Geology of the Olduvai Gorge*: *A Study of Sedimentation in a Semiarid Basin* (Hay, 1976). Along with Hay's stratigraphic studies, K-Ar dating was applied to date the Olduvai Gorge sequence (Evernden and Curtis, 1965). In Kenya, Glynn Isaac (1967) focused on investigating sedimentologic processes to interpret Acheulian occurrences at Olorgesailie, and Bill Farrand conducted geological research in the Baringo district of Kenya as part of an interdisciplinary team in 1973.

In Europe and the Middle East, Bill Farrand conducted studies of Paleolithic cave sequences at: Yabrud, Syria, in 1963–1964; Abri Pataud, France, in 1964–1965; Tabun Cave, Israel, in 1967–1972; and Franchthi Cave, Greece, in 1974 and 1975. As part of the Tabun project, the stratigraphy and sedimentology were studied by Paul Goldberg from 1967 to 1970; in 1966, he had served as a field assistant to Farrand studying loess in the Rhine Valley, France. In Greece during the 1960s, William McDonald included earth scientists in a survey of Messenia, bringing in Wright (who had previously collaborated in archaeological projects in Lebanon and Iraq), then George Rapp, Jr. in 1966. Field studies conducted by Chris Kraft, Stan Aschenbrenner, and Rapp from 1971 to 1975 focused on the paleogeography of the coastal plain of the southwestern Peloponnese, while the geology of the Bronze Age site of Nichoria was studied by Julie Stein (Stein and Rapp, 1978). The studies initiated by Kraft and Rapp in the 1970s turned into a long-term investigation of the ways coastal change has affected major archaeological sites in Greece and Turkey, such as Troy, Ephesus, ancient Pylos, and the landscape of the famous battle at Thermopylae. The model of multidisciplinary studies of archaeological sites in the Mediterranean was also applied at Tel Michal, Israel, in the late 1970s where geologic studies were conducted by John Gifford and Rapp with field assistance in 1978 from Christopher Hill (Gifford et al., 1989).

In North America, Vance Haynes conducted detailed investigations of the Blackwater Draw as part of the interdisciplinary High Plains Paleoecology Project organized by Fred Wendorf. This included studies of the Clovis type site in 1962. The stratigraphic and geochronological investigations initiated by Haynes in the 1950s and 1960s were the beginning of a series of significant contributions to research along the interface of the geosciences and archaeology. In North America, Haynes focused on the geologic contexts of Late Pleistocene and early Holocene sites using radiocarbon dating to (1) interpret the stratigraphy and setting of archaeological sites and (2) to revise the broader-scale alluvial chronologies developed by Antevs, Bryan, Miller, and others (Antevs, 1955; Haynes, 1964b; Haynes, 1968). In 1968, 1973, and 1975–1977, Haynes was a member of the CPE, which involved geologic studies in Egypt and Ethiopia. Haynes continued his Paleoindian research focus as well as studies of the Eastern Sahara throughout his prolific career, along the way training and mentoring several generations of geoarchaeologists or archaeological geologists. During the 1970s, John Albanese served as geologist for research teams investigating Paleoindian sites of the Great Plains, such as Casper, Agate Basin, and Colby, to name a few.

The overlap between geoarchaeology and landscape ecology is illustrated by the research of Pedro Armillas (1971) on the chinampas in the Valley of Mexico. This was part of a comprehensive project to study the human role in shaping the landscape. It provided a view of the landscape as a product of interaction between the natural environment and human behavior. Following on the concepts formulated by people such as Humboldt and Sauer, Armillas's studies were not at the scale of artifact or the immediate site, but they used archaeological data at the scale of landscape to evaluate modifications of the natural environment brought about by human activity. Although the studies were aimed at the interrelationships between humans and the environment, the goal was to examine how humans could modify the natural environment. This was in contrast to the prevailing focus of environmental archaeology at the time, which explored the natural aspects of human habitats.

The terms "geoarchaeology" and "archaeological geology" have also been used since the 1970s to designate the earth-science approach to archaeological studies as well as the use of archaeological occurrences to understand natural patterns and processes of the geological record. The term "geoarchaeological" was used in a paper on the site stratigraphy and sediments of an Acheulian spring site in South Africa (Butzer, 1973, 315) and "geoarchaeology" was used in the first article in the first volume of the *Journal of Archaeological Science* (Butzer, 1974). The deliberate connection of "geoarchaeology" to an ecological approach was advocated in a paper published in *American Antiquity*. Butzer suggested that the solution to developing "a more effective ecological interpretation of man's past" was for earth scientists to directly identify with the goals of archaeology by applying the label geoarchaeology (Butzer, 1975, 106).

A symposium on the theme of sediments in archaeology held at the University of Southampton in 1973 resulted in *Geoarchaeology*: *Earth Science and the Past* edited by Donald Davidson and Myra Shackley (1976). The book provided a view into what was considered the potential scope of the term "geoarchaeology." It was divided into sections on techniques, coastal and lacustrine environments, terrestrial environments, and biological sediments. Geoarchaeological techniques included the recording of sediments and their consideration as paleo-land segments, as well as specific techniques of material analysis used to examine sediments, soils, artifacts, and rock-shelters. The chapters devoted to environments evaluated archaeological sites at the scales of stratigraphic sections and landscapes, while paleobotanical and invertebrate studies were presented in the section on biological sediments.

One of the most insightful contributions in *Geoarchaeology* was Colin Renfrew's introductory chapter titled "Archaeology and the earth sciences." After describing the origin in the 1950s of archaeometry and bio-archaeology, he observed that there also had been developing "the emergence of a new discipline" with a focus on "soils, sediments, and landforms. . .primarily concerned with context" (Renfrew, 1976, 2). The questions to be answered by geoarchaeology, according to Renfrew, concerned the position of the site in time, processes of site formation and site location, and environment as part of an ecological framework connected with changes in landform and human use of resources. For Renfrew, geoarchaeological studies "bring into closer relationship the geomorphologist and physical geographer. . .and the human geographer and anthropologist" (1976, 5).

There were other efforts to delineate the research connections between geoscience and archaeology. The role of geologist as part of an archaeological team was described by Rapp (1975). Two papers published in *American Antiquity* serve to illustrate perceptions at this time. Bruce Gladfelter (1977) advocated a geomorphic, paleoenvironmental approach to geoarchaeology. He proposed a scheme that emphasized the depositional context at site-specific locations, local landscape (habitat), and regional scales. Fekri Hassan (1979) equated geoarchaeology with archaeological geology and advocated a broader view of the field, suggesting that the ultimate aim of geoarchaeology was to "provide an understanding of those key paleoenvironmental variables that were or could have been influential" within a human ecosystem (Hassan, 1979, 269). This ecologic perspective was also expressed in the environmental and interdisciplinary perspectives of Roald Fryxell (1977). Noting that anthropology is a synthetic discipline that draws from a diverse number of fields, Fryxell argued that anthropological training required an understanding of environmental interpretation and technical interdisciplinary skills.

Since the 1970s, opinions have consolidated regarding the importance of a natural-science perspective in archaeology and the value of geoarchaeology as a discipline embedded in the ecological approach to the study of human-environment relationships. Archaeological data appear as the product of varying proportions of human behavioral activities and the processes of nature. The dynamics and connections of the long-term past can be understood more fully when the environmental context and the processes involved in creating the archaeological record are empirically documented and evaluated. Butzer (1982, 11) advocated an ecologic or broadly contextual approach to archaeology that emphasized the application of geoarchaeology: "It has been said that archaeology is anthropology or it is nothing.... I beg to differ with this view. Archaeology. . .has been equally dependent on geology, biology, and geography. . .during its development. . . [and] is heavily dependent on . . .the natural sciences."

Geoarchaeology has sometimes been applied in a restricted way to describe the study and interpretation of sediments and physical landscapes as a way to connect landscape evolution and human activities. Robert Thorson (1990) viewed archaeological sites as geological localities with remains of interest to archaeologists. Reid Ferring (1994) emphasized the changes in archaeological perspectives since the emergence of processual archaeology and perceived geoarchaeology as an empirical approach to archaeological questions. Mike Waters (1992) applied the term geoarchaeology to studies of site stratigraphy, formation processes, and landscape-human interaction, as compared to archaeometry with its goals of archaeological prospecting, provenance, and dating. Rolfe Mandel (2000a) viewed geoarchaeology as employing geoscience methods and concepts to archaeological deposits and formation processes.

The history of the discipline of geoarchaeology is about its development over time, not only as it has been practiced or defined but also how it has emerged as a community of scientists organized and connected in the pursuit of understanding the long-term relationships between humans and the environment. Geoarchaeology as a discipline has been blessed by a cadre of "true believers" who have connected the strong but loose ends of the geosciences and archaeology and woven them into a resilient, dynamic field of interdisciplinary, ecological science. Progress toward this result began even before there was a named and recognized field of geoarchaeology or archaeological geology, but a more formal set of institutional arrangements has emerged since the 1970s. These structures provide mentoring and training in the skills needed to practice geoarchaeology; opportunities to interact, to compare experiences, and to disseminate and critique research; and a sense of intellectual tradition or heritage.

Professional groups and publications dedicated to geoarchaeology were established during the last part of the twentieth century. Members of the Geological Society of America (GSA) began to see the value of a forum for archaeologically related geological studies in the 1970s. At the 1973 GSA meeting, Vance Haynes and Harold Malde chaired a session on archaeological geology. The enhanced visibility of geological applications to archaeology led to a short article coauthored by George Rapp, Reuben Bullard, and Claude Albritton titled "Geoarchaeology?" (1974). After Rapp sent in a formal proposal to the GSA, the Archaeological Geology Division of the GSA was formed in 1977 with Rapp serving as Chair, and the Division's newsletter was first printed in 1978. The first volume of *Geoarchaeology*: *An International Journal* was published in 1986. The founding editor, Jack Donahue, credited Rhodes Fairbridge for suggesting a journal at the 1983 meeting of the GSA. In 1996, the Society for American Archaeology (SAA) put out a call for the formation of interest groups. Rolfe Mandel drafted a proposal that was reviewed by Julie Stein, and they submitted it to the SAA as co-organizers. Mandel served as the first Chair of the Geoarchaeology Interest Group from 1997 to 1998, and volume 1 of the newsletter was printed in 1998. Academic programs have also been established. By the early part of the twenty-first century, there were several officially designated master's and bachelor's degree programs in geoarchaeology. In retrospect, it was during the 1970s and 1980s that the *practice* of applying the earth sciences to the study of the human past had reached a threshold and the *discipline* of geoarchaeology had been established.

Summary

The use of an earth-science approach to evaluate the archaeological record began in the eighteenth and nineteenth centuries with an appreciation of "prehistoric" time and the development of basic principles for linking past and ongoing environmental processes. By the twentieth century, collaboration between earth scientists and ecologically oriented archaeologists had intensified with the convergence of goals and techniques. Throughout the history of interaction, ideas and methods originating with the geosciences have been used to study the processes involved in the formation of the sedimentary archaeological record, to measure and classify the physical characteristics of artifacts and geofacts, to develop chronological frameworks, and to infer the paleoenvironmental settings associated with archaeological sites. A fundamental component of geoarchaeology throughout its history has been its focus on human-environment relationships.

Geoarchaeology unites the study of the record of past human activity with the natural (physical and biological) sciences. Historically, the geoscience approach in archaeology has been applied to preparing for and conducting fieldwork and collecting field data, the choice and application of laboratory techniques, and the interpretation of human-environmental relationships. The types of archaeological questions that have been addressed by using earth-science approaches include: studies of environmental settings and natural resources linked to land use; predicting the location of archaeological sites; documenting sedimentological, stratigraphic, and landscape contexts; identifying and describing raw materials, sediments, and soils; site formation; dating; and ecological integration.

The history of using a geoscience approach to examine these questions began in the late 1700s and 1800s and is illustrated by a preliminary interest in human-earth interactions, stratigraphic chronology, and human antiquity. During the early part of the 1900s, there was a refinement in the application of stratigraphic principles to archaeological sites and an expansion of the use of geoscience-derived field and laboratory techniques in areas like the study of past environments and raw material analyses. Although the application of geoscience techniques and geoecological principles became more pervasive throughout the 1900s, a real turning point in the history of geoarchaeology occurred during the 1950s–1970s. By the 1970s, it had become clear that the use of geoscience was essential to understanding the connections between humans and the environment and to applying an empirical, contextual, and interdisciplinary approach to interpreting the archaeological record. From a historical perspective, geoarchaeology is ultimately an interdisciplinary, ecological science focused on the relationships that connect humans and environmental systems.

Bibliography

Albritton, C. C., Jr., and Bryan, K., 1939. Quaternary stratigraphy in the Davis Mountains, Trans-Pecos, Texas. *Geological Society of America Bulletin*, **50**(1), 1423–1474.

Antevs, E. V., 1935. The occurrence of flints and extinct animals in pluvial deposits near Clovis, New Mexico, Part II. Age of Clovis lake clays. *Proceedings of the Philadelphia Academy of Natural Sciences*, **87**, 304–311.

Antevs, E. V., 1955. Geologic-climate dating in the west. *American Antiquity*, **20**(4), 317–335.

Armillas, P., 1971. Gardens on swamps. *Science*, **174**(4010), 653–661.

Arnold, J. R., and Libby, W. F., 1949. Age determination by radiocarbon content: checks with samples of known age. *Science*, **110**(2869), 678–680.

Braidwood, R. J., 1957. Means toward an understanding of human behavior before the present. In Taylor, W. W. (ed.), *The Identification of Non-Artifactual Materials.* Washington, DC: National Academy of Sciences and National Research Council. National Research Council Publication 565, pp. 14–16.

Bryan, K., 1925. Date of channel trenching (arroyo cutting) in the arid Southwest. *Science*, **62**(1607), 338–344.

Bryan, K., 1954. *The Geology of Chaco Canyon, New Mexico in Relation to the Life and Remains of the Prehistoric Peoples of Pueblo Bonito*. Washington, DC: Smithsonian Institution. Smithsonian Miscellaneous Collections, Vol. 122, No. 7.

Bryan, K., and Ray, L. L., 1940. *Geologic Antiquity of the Lindenmeier Site in Colorado*. Washington, DC: Smithsonian Institution. Smithsonian Miscellaneous Collections, Vol. 99, No. 2.

Butzer, K. W., 1959a. Contributions to the Pleistocene geology of the Nile Valley. *Erdkunde*, **13**(1), 46–67.

Butzer, K. W., 1959b. Environment and human ecology in Egypt during Predynastic and Early Dynastic times. *Bulletin de la Société de Géographie d'Égypte*, **32**, 43–87.

Butzer, K. W., 1960. Archeology and geology in ancient Egypt. *Science*, **132**(3440), 1617–1624.

Butzer, K. W., 1964. *Environment and Archeology: An Introduction to Pleistocene Geography.* Chicago: Aldine.

Butzer, K. W., 1973. Spring sediments from the Acheulian site of Amanzi (Uitenhage District, South Africa). *Quaternaria*, **17**, 299–319.

Butzer, K. W., 1974. Geo-archeological interpretation of Acheulian calc-pan sites at Doornlaagte and Rooidam (Kimberley, South Africa). *Journal of Archaeological Science*, **1**(1), 1–25.

Butzer, K. W., 1975. The "ecological" approach to prehistory: are we really trying? *American Antiquity*, **40**(1), 106–111.

Butzer, K. W., 1982. *Archaeology as Human Ecology; Method and Theory for a Contextual Approach*. New York: Cambridge University Press.

Caton-Thompson, G., and Gardner, E. W., 1934. *The Desert Fayum*. Gloucester: John Bellows-Royal Anthropological Institute.

Cornwall, I. W., 1958. *Soils for the Archaeologist*. London: Phoenix House.

Crawford, O. G. S., 1923. Air survey and archaeology. *Geographical Journal*, **61**(5), 266–342.

Crawford, O. G. S., and Keiller, A., 1928. *Wessex from the Air*. Oxford: Clarendon Press.

Crutzen, P. J., 2002. Geology of mankind. *Nature*, **415**(6867), 23.

Davidson, D. A., and Shackley, M. L. (eds.), 1976. *Geoarchaeology; Earth Science and the Past*. Boulder: Westview Press.

Douglass, A. E., 1929. The secret of the Southwest solved by talkative tree rings. *National Geographic Magazine*, **56**(6), 736–770.

Evernden, J. F., and Curtis, G. H., 1965. The potassium-argon dating of Late Cenozoic rocks in East Africa and Italy. *Current Anthropology*, **6**(4), 343–385.

Ferring, C. R., 1994. Review of principles of geoarchaeology: a North American perspective. *American Anthropologist*, **96**(1), 218–219.

Fox, C., 1923. *The Archaeology of the Cambridge Region*. Cambridge: Cambridge University Press.

Fox, C., 1932. *The Personality of Britain*. Cardiff: The National Museum of Wales.

Frere, J., 1800. Account of flint weapons discovered at Hoxne in Suffolk. *Archeologia*, **13**, 204–205.

Fryxell, R., 1977. *The Interdisciplinary Dilemma: A Case for Flexibility in Academic Thought*. Rock Island, IL: Augustana College. Augustana College Library Occasional Paper 13.

Geikie, J., 1874. *The Great Ice Age and its Relation to the Antiquity of Man*. London: W. Isbister.

Gifford, J. A., Rapp, G. R., and Hill, C. L., 1989. Site geology. In Herzog, Z., Rapp, G. R., Jr., and Negbi, O. (eds.), *Excavations at Tel Michal, Israel*. Minneapolis/Tel Aviv: University of Minnesota Press/Tel Aviv University, pp. 209–218.

Gladfelter, B. G., 1977. Geoarchaeology: the geomorphologist and archaeology. *American Antiquity*, **42**(4), 519–538.

Hassan, F. A., 1979. Geoarchaeology: the geologist and archaeology. *American Antiquity*, **44**(2), 267–270.

Hay, R. L., 1963. Stratigraphy of beds 1 through 4, Olduvai Gorge, Tanganyika. *Science*, **139**(3557), 829–833.

Hay, R. L., 1976. *Geology of the Olduvai Gorge*. Berkeley: University of California Press.

Haynes, C. V., Jr., 1964a. The geologist's role in Pleistocene paleoecology and archaeology. In Hester, J. J., and Schonwetter, J. (eds.), *The Reconstruction of Past Environments*. Taos: Fort Burgwin Research Center, pp. 61–66.

Haynes, C. V., Jr., 1964b. Fluted projectile points: their age and dispersion. *Science*, **145**(3639), 1408–1413.

Haynes, C. V., Jr., 1968. Geochronology of late-Quaternary alluvium. In Morrison, R. B., and Wright, H. E., Jr. (eds.), *Means of Correlation of Quaternary Successions*. Salt Lake City: University of Utah Press, pp. 591–631.

Haynes, C. V., Jr., 1990. The Antevs-Bryan years and the legacy for Paleoindian geochronology. In Laporte, L. (ed.), *Establishment of a Geologic Framework for Paleoanthropology*. Boulder: Geological Society of America. GSA Special Paper 242, pp. 55–68.

Haynes, C. V., Jr., and Agogino, G., 1960. *Geological Significance of a New Radiocarbon Date from the Lindenmeier Site*. Denver: Denver Museum of Natural History. Proceedings 9.

Hill, C. L., 2005. Geoarchaeology. In Maschner, H. D. G., and Chippindale, C. (eds.), *Handbook of Archaeological Methods*. Lanham: Altamira Press, Vol. II, pp. 1002–1033.

Holliday, V. T., 1997. *Paleoindian Geoarchaeology of the Southern High Plains*. Austin: University of Texas Press.

Huntington, E., 1915. *Civilization and Climate*. New Haven: Yale University Press.

Huntington, E., 1917. Maya civilization and climatic changes. In *Proceedings of the 19th International Congress of Americanists*, October 5–10, 1914. Washington, DC: Smithsonian Institution, pp. 150–164.

Hutton, J., 1788. Theory of the earth. *Transactions of the Royal Society of Edinburgh*, **1**, 209–305.

Isaac, G. L., 1967. Towards the interpretation of occupation debris: some experiments and observations. *Kroeber Anthropology Society Papers*, **37**, 31–57.

Judson, S., 1953. *Geology of the San Jon Site, Eastern New Mexico.* Washington, DC: Smithsonian Institution. Smithsonian Miscellaneous Collections, Vol. 121, No. 1.

Judson, S., 1975. Geological and geographical setting. In Movius, H. L., Jr. (ed.), *Excavation of the Abri Pataud, Les Eyzies (Dordogne)*. Cambridge: Peabody Museum, Harvard University. American School of Prehistoric Research Bulletin, Vol. 30, pp. 19–26.

Kidder, A. V., 1924. *An Introduction to the Study of Southwestern Archaeology*. New Haven: Yale University Press.

Lapham, I. A., 1855. *Antiquities of Wisconsin: As Surveyed and Described*. Washington, DC: Smithsonian Institution. Smithsonian Contributions to Knowledge 7, Art. 4.

Lubock, J., 1865. *Pre-Historic Times*. London: Williams and Norgate.

Lyell, C., 1830–1833. *Principles of Geology*, 3 vols. London: John Murray.

Lyell, C., 1863. *Geological Evidences of the Antiquity of Man*. London: Murray.

MacCurdy, G. (ed.), 1937. *Early Man, as Depicted by Leading Authorities at the International Symposium, the Academy of Natural Sciences, Philadelphia*. Philadelphia: J. B. Lippincott.

Mandel, R. D., 2000a. Introduction. In Mandel, R. D. (ed.), *Geoarchaeology in the Great Plains*. Norman: University of Oklahoma Press, pp. 3–9.

Mandel, R. D. (ed.), 2000b. *Geoarchaeology in the Great Plains*. Norman: University of Oklahoma Press.

Marsh, G. P., 1874. *The Earth as Modified by Human Action: A New Edition of Man and Nature*. London: Sampson, Low, Marston, Low, Searle.

Movius, H. L., Jr., 1949. Old-world palaeolithic archaeology. *Bulletin of the Geological Society of America*, **60**(9), 1443–1456.

Movius, H. L., Jr., 1957. The Old World paleolithic. In Taylor, W. W. (ed.), *Identification of Non-Artifactual Archaeological Materials*. Washington, DC: National Academy of Sciences and National Research Council. National Academy of Sciences Publication 565, pp. 26–27.

Péwé, T. L., 1954. The geological approach to dating archaeological sites. *American Antiquity*, **20**(1), 51–61.

Powell, J. W., 1878. *Report on the Lands of the Arid Region of the United States*. Washington, DC: Government Printing Office.

Powell, J. W., 1890. Prehistoric man in America. *Forum*, **8**, 489–503.

Pumpelly, R., 1905. *Explorations in Turkestan*. Washington, DC: Carnegie Institution. Carnegie Institution Publication No. 26.

Pyddoke, E., 1961. *Stratification for the Archaeologist*. London: Phoenix House.

Rapp, G. R., 1975. The archaeological field staff: the geologist. *Journal of Field Archaeology*, **2**(3), 229–237.
Rapp, G. R., and Hill, C. L., 2006. *Geoarchaeology: The Earth-Science Approach to Archaeological Interpretation*, 2nd edn. New Haven: Yale University Press.
Rapp, G., Jr., Bullard, R., and Albritton, C., 1974. Geoarchaeology? *The Geologist, the Newsletter of the Geological Society of America*, **9**(1), 1.
Renfrew, C., 1976. Archaeology and the earth sciences. In Davidson, D. A., and Shackley, M. L. (eds.), *Geoarchaeology: Earth Science and the Past*. Boulder: Westview Press, pp. 1–5.
Sauer, C. O., 1925. The morphology of landscape. *University of California Publications in Geography*, **2**(2), 19–54.
Sauer, C. O., and Brand, D. D., 1932. *Aztatlán: Prehistoric Mexican Frontier on the Pacific Coast*. Berkeley: University of California Press.
Squier, E. G., and Davis, E. H., 1848. *Ancient Monuments of the Mississippi Valley*. Washington, DC: Smithsonian Institution.
Stein, J. K., and Rapp, G., Jr., 1978. Archaeological geology of the site. In Rapp, G., Jr., and Aschenbrenner, S. E. (eds.), *Excavations at Nichoria in Southwest Greece*. Minneapolis: University of Minnesota Press. Site, Environs, and Techniques, Vol. 1, pp. 234–257.
Stoppani, A., 1871–73. *Corso di Geologia*, 3 vols. Milan: Bernardoni e Brigola.
Thorson, R., 1990. Archaeological geology. *Geotimes* (February), 32–33.
Uhle, M., 1903. *Pachamac: Report of the William Pepper, M.D., LL. D., Peruvian Expedition of 1896*. Philadelphia: Department of Archaeology, University of Pennsylvania.
Uhle, M., 1907. *The Emeryville Shellmound*. Berkeley: University of California Press. University of California Publications in American Archaeology and Ethnology 7, Vol. 1.
von Humboldt, A., 1814. *Researches Concerning the Institutions and Monuments of the Ancient Inhabitants of America*. London: Longman, Vol. 2.
Waters, M. R., 1992. *Principles of Geoarchaeology: A North American Perspective*. Tucson: University of Arizona Press.
West, R. C., 1979. *Carl Sauer's Fieldwork in Latin America*. Ann Arbor: University Microfilms published for the Department of Geography, Syracuse University. Dellplain Latin American Studies 3.
Wheeler, M., 1954. *Archaeology from the Earth*. Oxford: Clarendon Press.
Wissler, C., 1924. The relation of Nature to man as illustrated by the North American Indian. *Ecology*, **5**(4), 311–318.
Zalasiewicz, J., Williams, M., Smith, A., Barry, T. L., Coe, A. L., Brown, P. R., Brenchley, P., Cantrill, D., Gale, A., Gibbard, P., Gregory, J. F., Hounslow, M. W., Kerr, A. C., Pearson, P., Knox, R., Powell, J., Waters, C., Marshall, J., Oates, M., Rawson, P., and Stone, P., 2008. Are we now living in the Anthropocene? *GSA Today*, **18**(2), 4–8.
Zeuner, F. E., 1945. *The Pleistocene Period; Its Climate, Chronology, and Faunal Successions*. London: B. Quaritch.
Zeuner, F. E., 1946. *Dating the Past: An Introduction to Geochronology*. London: Methuen.
Zeuner, F. E., 1952. *Dating the Past: An Introduction to Geochronology*, 3rd edn. London: Methuen.

Cross-references

Eastern Sahara: Combined Prehistoric Expedition
Gesher Benot Ya'aqov
Minnesota Messenia Expedition (MME)
Olduvai

GEOCHEMICAL SOURCING

Michael D. Glascock
Archaeometry Laboratory, Research Reactor Center, University of Missouri, Columbia, MO, USA

Introduction

Archaeologists who study past human societies do so by investigating the remains they left behind. One of the questions that is frequently asked about recovered finds is "Where did the artifacts come from?" Efforts to answer this question are often carried out in collaboration with colleagues from the physical and chemical sciences, and the evidence obtained is used to determine the locations (i.e., sources) of the raw materials that were used to produce the artifacts. Because instrumental measurements are usually required to address such matters, most of the work involved takes place in a laboratory environment. In some instances, measurements may be possible in situ within a field context.

Past humans preferred to live near the sources of raw materials needed for making artifacts. Those who lived far away made long journeys to obtain the raw materials, or they acquired raw materials or finished goods by indirect means (e.g., trade or exchange). Information about artifact and source material composition can help archaeologists infer past human behaviors for which no other documentation exists. Such behaviors may include the procurement of raw materials, mobility patterns, recognition of political boundaries, and competition for resources. Other applications of sourcing involve artifact authentication, development of technology, and collecting information in support of dating.

Sourcing studies make use of the chemical and physical properties of artifacts and source materials to trace artifacts from their findspot to their place of origin. In some cases, artifact sourcing involves visual methods based on characteristics such as color and texture. For example, lithic artifacts may have been made using source materials with distinctive colors or unique textures (e.g., streaks or inclusions). Inspection of petrographic thin sections of pottery or stone under a microscope sometimes permits the identification of minerals that can be traced to specific sources. Although visual methods of sourcing are less expensive than geochemical ones, they are too subjective and unreliable to use for the routine sourcing of large numbers of artifacts. Geochemical techniques offer more reliability, they can be automated, and they are quantitative, which means they can be validated by statistical procedures.

A basic understanding of geochemical sourcing should include a brief history of its use, an explanation of its principles, and a description of a systematic approach to characterizing sources and artifacts from which the obtained results will be both reliable and valid.

History of sourcing and the provenance postulate

According to a review of the early literature on archaeological chemistry by Caley (1951), the first report of a chemical analysis performed on artifacts of any type was made by the chemist Martin Heinrich Klaproth (1743–1817). Klaproth's work describing the analysis of several ancient Greek and Roman coins was read before the Académie Royale des Sciences et Belles-Lettres de Prusse in Berlin on July 9, 1795, and published in a volume of memoirs by the Royal Academy in 1798. Klaproth discovered that the coins in his study were made of pure copper or copper alloys, and he used this information to estimate their compositions. Because this type of work had never been done before, Klaproth is also recognized as a pioneer in the development of analytical methods in the study of ancient alloys.

Three years later, on October 4, 1798, Klaproth presented a second paper before the Royal Academy describing his investigation of three samples of Roman glass from a mosaic discovered in the ruins of the Villa of Tiberius at Capri. The samples were highly colored and opaque; one was red, one was green, and the third sample was blue. The main objective of his study was to determine the reasons for the different colors. By chemical analysis, he concluded that the different colors were due to the presence of copper and iron, and he also produced a nearly complete analysis of the major constituents. It is interesting to note that in both of Klaproth's works and in subsequent studies of glass by Sir Humphry Davy (1815), the main purpose was to increase understanding of ancient technology rather than to investigate the sources of the raw materials used.

A pamphlet by Göbel (1842) describes the first known attempt to examine a collection of artifacts with the goal of determining both the source and archaeological significance. Several brass artifacts excavated from the Russian Baltic provinces were analyzed, and their compositions were compared to prehistoric brass objects known to be of Greek and Roman origins. The similarity in composition to brass from the Roman Empire was used by Göbel to propose the interpretation that the objects were probably acquired by trade.

Following work by Damour (1865), chemists began to study archaeological materials other than metals and glass. Damour determined the density and composition of rocks and stones for the purpose of establishing their origin. A chemical analysis by Fouqué (1869) of pottery from the island of Santorini concluded that local clay sources had been exploited for pottery production on the island.

Throughout the remainder of the nineteenth and into the first half of the twentieth century, analytical chemists continued to be interested mainly in the compositions of ancient glass and coins. They employed methods such as optical emission spectrometry (OES) or atomic absorption spectrometry (AAS). Use of these methods was limited by the labor demands because the samples required tedious dissolutions, and constituent elements could be measured only one at a time. Other than studying technology and artifact authentication, these works did very little to advance the practice of geochemical sourcing.

The first application of neutron activation analysis (NAA) to archaeological materials occurred in the 1950s. Sayre and Dodson (1957) discovered that the Mn-to-Na ratios in potsherds from several locations in the Mediterranean region (Asia Minor, Greece, and Italy) had similar compositional profiles when they came from the same place of manufacture, but distinctly different profiles when they came from different sources. Soon afterward, Emeulus (1958) used NAA to produce a comprehensive fingerprint for Samian ware potsherds from the western Mediterranean by measuring the major, minor, and the trace elements, simultaneously.

The first geochemical study of obsidian was conducted by Cann and Renfrew (1964), who used OES to examine obsidian from sources located in Anatolia, Africa, and the Mediterranean. This work demonstrated that sources from the different regions differed chemically and that specimens from yet other regions were also different in composition. Heizer et al. (1965) employed X-ray fluorescence (XRF) to identify the sources of obsidian artifacts from sites in Mesoamerica. Soon afterward, Griffin and Gordus (1967) used NAA to determine that prehistoric obsidian tools found on Hopewell sites in Ohio came from sources located in Wyoming and Idaho.

As the instrumentation and procedures for NAA gradually improved, scientists at the Lawrence Berkeley National Laboratory (Perlman and Asaro, 1969, 1971) described a standard comparator procedure for routine sourcing work on ceramic materials based on the use of a homemade pottery standard. With the development of other reliable standard reference materials (SRMs) by the United States Geological Survey (USGS), the National Institute of Standards and Technology (NIST), and their counterparts in other countries (see below), NAA procedures similar to those of Perlman and Asaro were employed at the Brookhaven National Laboratory (BNL) by Bieber et al. (1976) and at many other NAA laboratories around the world (Speakman and Glascock, 2007).

NAA has been regarded as one of the most reliable techniques for geochemical sourcing studies because of its precision and accuracy. (Precision is a measurement of the reproducibility of an analysis, i.e., how consistent the results of analysis are over repeated trials. Accuracy is a measurement of the correctness of the analytical results; i.e., how close analysis gets to the true value.) NAA also has advantages for automation, which enables large numbers of samples to be analyzed systematically. The main drawbacks to NAA are that sample preparation is destructive and radioactive waste is produced.

Since the 1960s, several other analytical methods have been employed to characterize trace and minor elements present in a variety of archaeological materials. The earliest reported study using particle induced X-ray emission (PIXE) on archaeological materials by Ahlberg et al. (1976) was a study of gold alloys on the surface of slate. The first use of electron microprobe analysis (EMPA) on archaeological materials by Merrick and Brown (1984) involved sourcing obsidian artifacts from East Africa. In recent years, various types of inductively coupled plasma-mass spectrometry (ICP-MS) have been employed for bulk and surface analysis of archaeological samples. For example, microwave digestion (i.e., MD-ICP-MS) was used by Pingitore et al. (1997) to study prehistoric ceramic samples from the El Paso area, and laser ablation (i.e., LA-ICP-MS) was used by Gratuze (1999) to identify the sources of obsidian artifacts from Turkey. More recently, the convenience of handheld XRF spectrometers for rapid, nondestructive, on-site analysis of archaeological materials has gained widespread recognition (Williams-Thorpe et al., 1999).

The use of isotope-ratio mass spectrometry (IRMS) has grown in popularity in recent years. Sourcing applications with isotope ratios rely on the isotopic variations arising from mass-dependent fractionation of the light stable isotopes (e.g., of H, C, O, N, S) in natural systems or changes in isotopic ratios for the decay-product isotopes (e.g., of Sr and Pb) populated by the naturally radiogenic isotopes of Rb, Th, and U. Archaeological applications for IRMS include the use of gas source mass spectrometry (GSMS) of foods (Evershed et al., 2002) and human artifacts to measure oxygen isotope ratios, which can vary by latitude. Strontium isotope analysis has proven to be a successful method for studying human migration and mortuary rituals in the Andes region of South America (Knudson et al., 2004), and lead isotope ratios have been used to study lead exchange and provenance patterning in Southeast Asia (Pryce et al., 2011).

Although the prerequisites for sourcing of artifacts were clearly understood by the early analytical chemists, it was not until the mid-1970s that a precise description of the requirements was made. In a study of turquoise artifacts and sources from the American Southwest (Weigand et al., 1977), the authors state that success in linking artifacts to their true sources is dependent on the hypothesis "that there [must] exist differences in chemical composition between different natural sources that exceed, in some recognizable way, the differences observed within a given source." In other words, for a sourcing study to be successful, the between-source difference for the raw material must be greater than the within-source variation. The hypothesis is commonly referred to as the Provenance Postulate. The requirements described by the Provenance Postulate apply to any study involving chemical, mineralogical, and/or isotopic differences between sources.

What is a source?

Unfortunately, use of the term "source" can be ambiguous. When geologists use the term "source," they are usually referring to a specific geographic location for a particular material. On the other hand, geochemists describe a "source" on the basis of its chemical composition, which must be different from the composition of other sources. The former implies a geographic exactness, while the latter emphasizes the distinctiveness of a chemical type or "chemical group." Another way to imagine this distinction is that a geographic source is defined by its coordinates; but a geochemical source is defined by the composition of a group of samples which may have been dispersed spatially due to dynamic processes such as erosion and landform change.

As explained by Harbottle (1982), Hughes (1988), and Neff (1998), the two definitions correspond to different analytical units which, depending on the archaeological and geological circumstances and on the degree of resolution, may vary in their relevance to answering a specific archaeological question.

Raw material sources can be very complex. Primary deposits can range in size from a few tens of square meters to thousands of km^2. The materials from a source can have chemical fingerprints that are very homogeneous (e.g., obsidian) or highly heterogeneous (e.g., marble). As a result of natural geologic processes, primary sources are sometimes separated by tens of kilometers due to the emergence of mountain ranges or the incision of valleys, yet still reveal a single compositional signature for the entire source area. Fluvial transport processes can move raw materials hundreds of kilometers, thereby establishing displaced secondary deposits of essentially the same source (Shackley, 1995). Sources can also contain overlapping mixtures of raw materials representing several distinct chemical types (Ambroz et al., 2001).

In addition to the natural geologic processes that sometimes affect the locations and compositions of raw materials, other factors can make it very challenging to link artifacts geochemically to raw material sources. Among these factors are (1) modifications to the raw materials by technological, chemical, or biological processes at the moment of artifact production, (2) uses for artifacts that have the potential to induce changes in composition after manufacture, and (3) changes to artifact composition induced by postdepositional processes. Manufacturing practices, such as mixing, firing, or smelting, may alter the composition by enriching certain elements while diluting others; such activities can result in the production of artifacts (e.g., ceramics, glass, metals) that possess chemical signatures differing markedly from those of the original ingredients. The composition of artifacts can be altered by the incorporation of residues within the sample matrix during use or by diagenetic effects that occur after disposal and burial. Also, biological processes that create biofacts (e.g., bones, teeth, coprolites) convert food sources into plant or animal tissue; as artifactual indicators of past human behavior, these biofacts will be chemically different from their source materials.

Different approaches to source determination

As explained by Neff (2000), identifying a source based on the Provenance Postulate will generally follow either of two lines of attack. The two approaches differ according to whether compositional groups are defined through analysis of the source materials or the unknown artifacts. Sampling procedures and interpretation of the data will depend upon which approach is used.

The first approach is followed when the artifacts to be sourced were manufactured from natural materials by physical modification methods such as knapping, carving, or shaping. The raw materials may be compositionally homogeneous, such as most obsidians, or more heterogeneous, such as basalt, chert, limestone, and gemstones. Because artifact composition is not altered during manufacture, the compositional signatures remain essentially unchanged from those of the natural sources. In such cases, the sources should be analyzed first in order to establish the range of variation within, and differences between, the compositional reference groups for all available sources. Ideally, the reference groups should have some relationship to the primary geographic location of the source, but geological processes that displace raw materials may create secondary locations or mixtures of raw materials corresponding to multiple primary sources. After the source reference groups have been established, artifacts can be analyzed and compared to the reference groups to find the best matches.

The second approach is more often employed when the artifacts were made by technological, chemical, or biological modification of source materials or when the sources are so widespread that sampling all of them is impractical. Examples include artifacts such as ceramics, bricks, man-made glass, metals produced by smelting of raw ores, and biofacts. For this second approach, compositional reference groups are usually created by analyzing large numbers of artifacts. Artifact reference groups may reveal some relationship to archaeological sites, time periods, or other characteristics, but such associations do not necessarily emerge. Information regarding the frequencies of particular compositional groups present at archaeological sites is used to suggest whether the archaeological site is a production center or a use site (Bishop et al., 1982). The final step involves projecting the raw material sample compositions against the artifact reference groups and inferring the most likely locations for the raw materials used to manufacture the artifacts. Alternatively, artifact reference groups (e.g., for pottery and bricks) can be compared to other similar artifacts for which there is a known place of manufacture (such as sherd wasters from a potter's kiln or bricks from a former brickyard) in order to establish a location of production if not raw material source.

A systematic approach to characterization of sources

Reviews of the early literature on sourcing investigations indicate that many of the studies did not realize their full potential because they were poorly planned, poorly executed, or poorly communicated (Hughes, 1984; Glascock et al., 1998; Shackley, 1998). The problems ranged from: (1) incomplete source descriptions that failed to account for all possible primary and secondary deposits before assigning artifacts, (2) failure to collect and analyze a sufficient number of samples to describe the full variability within and differences between sources, and (3) analytical deficiencies that produced results that were incompatible with data from other studies or laboratories and therefore could not be broadly compared. As pointed out by Glascock et al. (1998), a well-planned, systematic approach to sourcing investigations can be more efficient, be less expensive, and realize greater potential.

The locations of raw material sources in the region of interest should be identified first. Through studies of geologic and topographic maps and on-the-ground surveys, the primary outcrops, secondary deposits, and prehistoric quarries should be investigated. Observations regarding erosion, weathering, volcanic activity, farming, and road cuts should be noted, because the landscape may have undergone significant changes since prehistoric times. The locations where prehistoric sources were formerly exploited may now be buried, or new source areas that were never used prehistorically may now be exposed. All available descriptive information should be recorded on the geologic setting, along with the geographic coordinates for samples collected at the source. Different names may be attributed to the same source, and therefore, clarification of all names used to describe the sources of raw materials is essential to avoid confusion by other archaeologists as well as the laboratory analysts, who are unlikely to have been engaged in the field collecting. Days or weeks of field reconnaissance, discussions with geologists, and consultations with the local populace may be necessary to complete an effective sample survey.

Raw material samples should be collected intensively throughout the source area so that enough specimens are available to detect and identify possible sub-sources. A handful of samples may be sufficient to assess internal variability within a homogeneous, localized obsidian source; however, one never knows until chemical analysis is completed and the results are assessed how many samples will be enough. There is no magic number of samples that should be collected and analyzed. Since it may be difficult or expensive to make multiple visits to collect additional samples, it is preferable to collect too many than too few. When sources cover large geographic areas and show substantial internal variation, and when outcrops are numerous, it may be necessary to collect hundreds of samples.

Samples collected for analysis should be representative of raw materials likely to have been used to manufacture artifacts. The size (i.e., mass) of individual samples should be large enough so that multiple analytical techniques can be conducted, and archival portions can be retained to allow for future analyses or for exchanges with colleagues from other laboratories. All details regarding the handling of samples should be recorded. Information regarding the tools used to extract raw materials, containers used to transport them, equipment used to grind them, chemicals used to digest them, and vessels used during chemical analysis should be documented so that potential sources of contamination can be recognized. All available analytical methods should be performed on the samples from each source so that the compositional data will have the highest possible precision and accuracy.

Calibration curves assign a value to a variable; they show the relationship between the analytical signal yielded by an instrumental technique and the quantity of an element present in the sample. Such curves are usually established by analyzing a series of primary standard reference materials (SRMs), including those available from the National Institute of Standards and Technology (NIST), United States Geological Survey (USGS), Geological Survey of Japan (GSJ), and other providers. The chemical uniformity of each standard means that it should always give very similar results for constituent elements, even when analyzed by different instruments, by different laboratories, by different techniques, and in different sample batches. The standards employed should be similar to the archaeological materials representing the unknowns, and when the standards are analyzed alongside the unknowns as quality control samples, they would indicate some form of bias if the results obtained for the standards varied from their predetermined values. Standards are routinely included in batches of samples to insure that no systematic errors are affecting accuracy and that consistent yields for a suite of elements confirm an acceptable level of precision.

Once analytical results have been obtained, examination of sample data for a range of sources using univariate and multivariate statistical methods (e.g., box-and-whisker plots, cluster analysis, factor analysis, principal components analysis, discriminant functions, bivariate plots, etc.) should be performed to identify compositional groups. Such groups represent clusters of samples that show similar chemical makeup; they will usually be associated with specific geographic coordinates, but they do not always turn out to be spatially constrained. Individual compositional groups should be described by approximately three times as many samples as the number of parameters (i.e., elements, minerals, isotope ratios, principal components, or factors) necessary to differentiate between the individual source groups (Harbottle, 1976). Careful examination of compositional group profiles may help to detect critical parameters (i.e., elements or combinations of elements that are distinctive and hold constant throughout one group but are absent in other groups and might thus be used as a shortcut). If critical parameters are discovered, it may be possible to design abbreviated analytical procedures that target specific measurements of those critical parameters. Use of abbreviated procedures has the potential to make analysis of certain artifacts more efficient and less expensive (Glascock et al., 1994).

Summary

Geochemical sourcing of artifacts has proven to be one of the most effective ways of identifying past human activities, including resource procurement practices, mobility patterns, trade and exchange, and recognition of political boundaries. Geochemical sourcing makes use of the compositional fingerprints of artifacts and source materials as measured by chemical, isotopic, or mineralogic methods, and the data obtained can be used to trace artifacts from their findspot to their place of origin, or source. The analytical techniques in most frequent use today are NAA, XRF, and ICP-MS, each of which are capable of measuring the abundances of elements and isotopes in a wide range of archaeological materials with high precision and accuracy.

In order for artifact sourcing studies to be successful, the most important requirement is that the source materials satisfy the Provenance Postulate, which requires that the compositional differences between sources be greater than the compositional variability within each source. Before analyzing large numbers of artifacts, it is essential that one undertake a systematic study in order to collect and analyze large numbers of source materials from all likely source areas (i.e., primary and secondary) to establish a reliable database against which the artifacts can be compared. Source and artifact data should be analyzed by a combination of univariate and multivariate statistical methods, including cluster analysis, principal components analysis, discriminant functions, and other methods to validate the robustness of any source assignment.

Evidence for the popularity of geochemical sourcing is demonstrated by the hundreds of articles that have appeared in journals such as *Archaeometry*, *Geoarchaeology*, *Journal of Archaeological Science*, and others over the past half century. A few recent examples of sourcing studies have been reported on human skeletal material, obsidian, ceramics, and chert, respectively, by Knudson et al. (2004), Glascock (2002, 2010), Anderson et al. (2011), and Huckell et al. (2011).

Bibliography

Ahlberg, M., Akselsson, R., Forkman, B., and Rausing, G., 1976. Gold traces on wedge-shaped artefacts from the late Neolithic of southern Scandinavia analysed by proton induced X-ray emission spectroscopy. *Archaeometry*, **18**(1), 39–42.

Ambroz, J. A., Glascock, M. D., and Skinner, C. E., 2001. Chemical differentiation of obsidian within the Glass Buttes complex, Oregon. *Journal of Archaeological Science*, **28**(7), 741–746.

Anderson, S. L., Boulanger, M. T., and Glascock, M. D., 2011. A new perspective on late Holocene social interaction in northwest Alaska: results of a preliminary ceramic sourcing study. *Journal of Archaeological Science*, **38**(5), 943–955.

Bieber, A. M., Jr., Brooks, D. W., Harbottle, G., and Sayre, E. V., 1976. Application of multivariate techniques to analytical data on Aegean ceramics. *Archaeometry*, **18**(1), 59–74.

Bishop, R. L., Rands, R. L., and Holley, G. R., 1982. Ceramic compositional analysis in archaeological perspective. In Schiffer, M. B. (ed.), *Advances in Archaeological Method and Theory*. New York: Academic Press, Vol. 5, pp. 275–330.

Caley, E. R., 1951. Early history and literature of archaeological chemistry. *Journal of Chemical Education*, **28**(2), 64–66.

Cann, J. R., and Renfrew, C., 1964. The characterization of obsidian and its application to the Mediterranean region. *Proceedings of the Prehistoric Society*, **30**, 111–133.
Damour, A. A., 1865. *Sur la composition des haches en pierre trouvées dans les monuments celtiques et chez les tribus sauvages*. Comptes rendus de l'Académie des sciences LXI, séances du 21 et 28 août 1865. Paris: Libairie académique, Didier et Cie, pp. 1–13.
Davy, H., 1815. Some experiments and observations on the colours used in painting by the ancients. *Philosophical Transactions of the Royal Society of London*, **105**, 97–124.
Emeulus, V. M., 1958. The technique of neutron activation analysis as applied to trace element determination in pottery and coins. *Archaeometry*, **1**, 6–15.
Evershed, R. P., Dudd, S. N., Copley, M. S., Berstan, R., Stott, A. W., Mottram, H., Buckley, S. A., and Crossman, Z., 2002. Chemistry of archaeological animal fats. *Accounts of Chemical Research*, **35**(8), 660–668.
Fouqué, F., 1869. Une Pompéi antéhistorique. *Revue des Deux Mondes*, **83**, 923–942.
Glascock, M. D., 2002. Obsidian provenance research in the Americas. *Accounts of Chemical Research*, **35**(8), 611–617.
Glascock, M. D., 2010. Comparison and contrast between XRF and NAA: used for characterization of obsidian sources in central Mexico. In Shackley, M. S. (ed.), *X-ray Fluorescence Spectrometry (XRF) in Geoarchaeology*. New York: Springer Verlag, pp. 161–192.
Glascock, M. D., Neff, H., Stryker, K. S., and Johnson, T. N., 1994. Sourcing archaeological obsidian by an abbreviated NAA procedure. *Journal of Radioanalytical and Nuclear Chemistry*, **180**(1), 29–35.
Glascock, M. D., Braswell, G. E., and Cobean, R. H., 1998. A systematic approach to obsidian source characterization. In Shackley, M. S. (ed.), *Archaeological Obsidian Studies: Method and Theory*. New York: Plenum. Advances in Archaeological and Museum Science, Vol. 3, pp. 15–65.
Göbel, K. C. T. F., 1842. *Über den Einfluss der Chemie auf die Ermittelung der Völker der Vorzeit: oder Resultate der chemischen Untersuchung metallischer Alterthümer*. Erlangen: Enke.
Gratuze, B., 1999. Obsidian characterization by laser ablation ICP-MS and its application to prehistoric trade in the Mediterranean and the Near East: sources and distribution of obsidian with the Aegean and Anatolia. *Journal of Archaeological Science*, **26**(8), 869–881.
Griffin, J. B., and Gordus, A. A., 1967. Neutron activation studies of the source of prehistoric Hopewellian obsidian implements from the Middle West. *Science*, **158**(3800), 528.
Harbottle, G., 1976. Activation analysis in archaeology. In Newton, G. W. A. (ed.), *Radiochemistry*. London: Chemical Society, Vol. 3, pp. 33–72.
Harbottle, G., 1982. Chemical characterization in archaeology. In Ericson, J. E., and Earle, T. K. (eds.), *Contexts for Prehistoric Exchange*. New York: Academic Press, pp. 13–51.
Heizer, R. F., Williams, H., and Graham, J., 1965. Notes on Mesoamerican obsidians and their significance in archaeological studies. In *Sources of Stones Used in Prehistoric Mesoamerican Sites*. Contributions of the University of California Archaeological Research Facility 1. Berkeley: Department of Anthropology, University of California, Berkeley, pp. 94–103.
Huckell, B. B., Kilby, J. D., Boulanger, M. T., and Glascock, M. D., 2011. Sentinel butte: neutron activation analysis of White River Group chert from a primary source and artifacts from a Clovis cache in North Dakota, USA. *Journal of Archaeological Science*, **38**(5), 965–976.
Hughes, R. E., 1988. The Coso volcanic field reexamined: implications for obsidian sourcing and hydration dating research. *Geoarchaeology*, **3**(4), 253–265.
Hughes, R. E. (ed.), 1984. *Obsidian Studies in the Great Basin*. Contributions of the University of California Archaeological Research Facility 45. Berkeley: Archaeological Research Facility, Department of Anthropology, University of California.
Knudson, K. J., Price, T. D., Buikstra, J. E., and Blom, E. D., 2004. The use of strontium isotope analysis to investigate Tiwanaku migration and mortuary ritual in Bolivia and Peru. *Archaeometry*, **46**(1), 5–18.
Merrick, H. V., and Brown, F. H., 1984. Rapid chemical characterization of obsidian artifacts by electron microprobe analysis. *Archaeometry*, **26**(2), 230–236.
Neff, H., 1998. Units in chemistry-based ceramic provenance investigations. In Ramenofsky, A. F., and Steffen, A. (eds.), *Unit Issues in Archaeology: Measuring Time, Space, and Material*. Salt Lake City: University of Utah Press, pp. 115–127.
Neff, H., 2000. Neutron activation analysis for provenance determination in archaeology. In Ciliberto, E., and Spoto, G. (eds.), *Modern Analytical Methods in Art and Archaeology*. New York: John Wiley, pp. 81–134.
Perlman, I., and Asaro, F., 1969. Pottery analysis by neutron activation. *Archaeometry*, **11**(1), 21–38.
Perlman, I., and Asaro, F., 1971. Pottery analysis by neutron activation. In Brill, R. H. (ed.), *Science and Archaeology*. Cambridge, MA: M.I.T. Press, pp. 182–195.
Pingitore, N. E., Jr., Hill, D. V., Villalobos, J., Leach, J., and Peterson, J. A., 1997. ICP-MS isotopic signatures of lead ceramic glazes, Rio Grande Valley, New Mexico, 1315-1700. In Vandiver, P. B., Druzik, J. R., Merkel, J. F., and Steward, J. (eds.), *Materials Issues in Art and Archaeology V*. Symposium Proceedings, Vol. 462. Pittsburgh: Materials Research Society, pp. 217–228.
Pryce, T. O., Brauns, M., Chang, N., Pernicka, E., Pollard, A. M., Ramsey, C., Rehren, T., Souksavatdy, V., and Sayavongkhamdy, T., 2011. Isotopic and technological variation in prehistoric Southeast Asian primary copper production. *Journal of Archaeological Science*, **38**(12), 3309–3322.
Sayre, E. V., and Dodson, R. W., 1957. Neutron activation study of Mediterranean potsherds. *American Journal of Archaeology*, **61**(1), 35–41.
Shackley, M. S., 1995. Sources of archaeological obsidian in the greater American Southwest: an update and quantitative analysis. *American Antiquity*, **60**(3), 531–551.
Shackley, M. S. (ed.), 1998. *Archaeological Obsidian Studies: Method and Theory*. New York: Plenum Press. Advances in Archaeological and Museum Science, Vol. 3.
Speakman, R. J., and Glascock, M. D., 2007. Acknowledging fifty years of neutron activation analysis in archaeology. *Archaeometry*, **49**(2), 179–183.
Weigand, P. C., Harbottle, G., and Sayre, E. V., 1977. Turquoise sources and source analysis: Mesoamerica and the southwestern USA. In Earle, T. K., and Ericson, J. E. (eds.), *Exchange Systems in Prehistory*. New York: Academic Press, pp. 15–34.
Williams-Thorpe, O., Potts, P. J., and Webb, P. C., 1999. Field-portable non-destructive analysis of lithic archaeological samples by X-ray fluorescence instrumentation using a mercury iodide detector: comparison with wavelength-dispersive XRF and a case study in British stone axe provenancing. *Journal of Archaeological Science*, **26**(2), 215–237.

Cross-references

Ceramics
Inductively Coupled Plasma-Mass Spectrometry (ICP-MS)

Lithics
Neutron Activation Analysis
Oxygen Isotopes
Scanning Electron Microscopy (SEM)
X-ray Fluorescence (XRF) Spectrometry in Geoarchaeology

GEOGRAPHICAL INFORMATION SYSTEMS (GIS)

Kenneth L. Kvamme
Department of Anthropology, University of Arkansas, Fayetteville, AR, USA

Synonyms

Geographic information systems; Geospatial information systems

Definition

GIS are software programs for creating, managing, manipulating, analyzing, modeling, and presenting spatially distributed information.

Introduction

GIS are complex software systems that enable one to encode, manage, and display information that has a spatial component; they also offer tools for data editing, manipulation, spatial analysis, and modeling. Included as well are components for database management, advanced graphics and cartography, image processing, and statistical analysis. Many benefits arise from these closely linked software systems, but GIS possess unique capabilities because all information is spatially referenced. This permits diverse data sets – environmental, social, land use, political – to be compared at any location. The results of queries, analyses, or models occur in map form, facilitating visualization of relationships. The synergy that results has promoted rapid growth of GIS applications in virtually all spatially oriented disciplines. This is particularly true in archaeology with its focus on site distributions within regions and artifact distributions within sites. Mapped information is not confined to Earth features or even to human scales because applications may range from atomic surfaces to galactic distributions and mappings of other planetary bodies.

Archaeological applications

GIS have a long history in archaeology beginning with the origins of the technology in the 1980s, represented by several papers in the Computer Applications in Archaeology conference proceedings and a major review article (Kvamme, 1989). Since then, the importance of GIS to the discipline is revealed by countless overview and research articles that illustrate multiple uses of the technology (e.g., see Allen et al., 1990; Lock and Stančič, 1995; McCoy and Ladefoged, 2009) and instructional textbooks (Wheatley and Gillings, 2002; Conolly and Lake, 2006). As in any field, the principal archaeological application of GIS is for database management. In archaeology, this refers to site-specific, state-wide, or regional databases typically used for cultural resource management (CRM) purposes, but also for research. Archaeological site files may include tens of thousands of archaeological records that must be managed. In these contexts, GIS are primarily employed for searches and queries, data displays, and reporting. GIS are also commonly used for managing projects that focus on a single archaeological site and which include historic and recent maps, records of excavated finds, imagery from geophysical surveys, aerial and satellite data, and digital elevation models (DEM).

More exciting are archaeological applications of GIS analytical tools for spatial analyses and problem solving. GIS have been employed to model prehistoric routes of travel over the landscape (Madry and Rakos, 1996) and to define territories and catchments around settlements based on resource distributions, natural boundaries, and travel time models (Gaffney and Stančič, 1991). Studies of intervisibility between settlements have been conducted to explain their settings, the dominance of some sites that command large regions of view, or socially important landscapes by the regions they define (Wheatley, 1995). GIS have enhanced prehistoric computer simulations by permitting them to function in realistic landscapes containing multidimensional features of actual environments (see papers in Kohler and van der Leeuw, 2007). GIS-based "predictive" models of archaeological location indicate regions where past settlement is likely to have occurred. They are typically based on extant data from known settlements, preferably taken from surveys that utilized some sort of regional random sampling scheme to reduce past survey biases. These settlements are analyzed for location preferences, such as tendencies for good soils, proximity to water, level ground, defensive positions on hilltops, etc. A wide variety of GIS techniques, ranging from simple Boolean intersections to complex logistic regression models, are then employed to combine these preferences into region-wide maps that describe spatial patterns of past settlement. The element of "prediction" arises when such maps permit prospecting for sites not yet discovered by traditional field surveys (see Mehrer and Wescott, 2005).

Software and hardware

The organization of GIS can be characterized as having four components: (1) a data input system that permits capture of information from maps, photographs, remote sensing devices, and databases; (2) a spatially organized data storage and retrieval system that allows rapid access and display of information using spatial or attribute searches while providing basic editing and updating functions; (3) a variety of geographical, image, and statistical processing routines for data manipulation and analysis, plus routines for transforming and aggregating information to produce new data as well as statistical analyses, summaries, and models; and (4) a reporting system that displays all or parts of the database in multiple graphical forms and in tables, charts, and graphs.

GIS databases can be large, so storage space and processing speed are issues, and high-resolution color graphics monitors are essential. Because the focus is on mappable information, specialized input and output devices are required, such as digitizers, scanners, and large-format color plotters. Popular GIS used in archaeology currently include ArcMap, TerrSet, MapInfo, GeoMedia, Grass, QGIS, and gvSIG.

Key concepts

Several concepts are fundamental to all GIS. One is "database region," which defines a window describing the space of interest, whether it is continental in scale, statewide, the area of an archaeological site, or even a single square meter of excavation. Individual mapped data sets represent distinct "layers" of information, each representing a spatially distributed variable for the region in question, such as hydrological drainage, population density, vegetation cover, etc. Layers may contain discrete objects that have size and shape (e.g., rivers, roads, buildings), or they may vary continuously as surfaces composed of numeric measurements (e.g., temperatures, elevations).

All positional data are defined by a coordinate system (e.g., Cartesian x-y, longitude-latitude), and individual layers are co-registered to the same coordinate system; this insures that any locus in one layer coincides with the same place in others. Additionally, GIS databases may be associated with a particular projection, which is necessary for large regions where the curved surface of a planetary sphere must be transformed in order to be projected onto a two-dimensional display (e.g., Universal Transverse Mercator, Albers Equal Area Conic).

The data that form the layers may be derived from digitized or scanned paper maps, global positioning system coordinates, aerial or satellite imagery, or geophysical instruments, for example. The processing power of GIS permits a great diversity of new layers to be derived. Such secondary layers may include processed and classified satellite data, terrain form measures derived from basic elevation data, or complex multivariate models based on numerous inputs.

Map data and GIS types

In cartography, maps are composed of discrete elements (including point, line, or area objects symbolizing lakes, roads, houses, towns), plus surfaces (e.g., a shaded terrain surface). Point features might represent a mountain summit, a surveyor's datum, or a town on a small-scale map. Lines are employed to indicate rivers or roads on small-scale maps, or elevation contours at any scale. Area data include lakes, forests, property parcels, or counties. The boundaries of areas form polygons. Surface data represent measurements that do not relate to arbitrary area units (such as counties), but to continuous variations that can be quantified anywhere. Examples include elevations, geomagnetic data, or continent-wide temperature changes. Two approaches to GIS have developed in response to these data types: "vector GIS" are designed for handling discrete point, line, or area objects, while "raster GIS" are best suited for continuous surface data. Each has very different characteristics, but most GIS permit work in both domains, and information can frequently be transformed from one to the other.

Raster GIS

A raster data structure is defined when measurements occur systematically across a region in a matrix composed of rows and columns. Location is controlled by row and column position within the raster where each cell is linked with real-world spatial coordinates. The attribute held in a particular cell of a raster grid represents the measurement corresponding to a specific area on the ground. In image or picture data, cells in a raster are frequently referred to as "pixels" (for "picture elements"). Raster layers are well suited for representing surface phenomena that vary continuously across a region, such as temperature, magnetic fields, terrain elevations, or reflected light variations in a satellite image or photo. Virtually all data from remote sensing occur in raster formats. Displays simply color-code or grayscale each cell, which can attain a photographic quality when all pixels are assembled.

Attributes held within cells may be continuous or categorical. The former may hold individual elevation measurements distributed every 10 m across a region to form a DEM of terrain, while the latter might portray soil distributions with numeric codes that indicate soil type. This means that raster GIS may hold discrete point, line, and area data types indicated by appropriate attribute codes in each cell. Accuracy is controlled by the area represented by a cell, which defines spatial resolution. The portrayal of discrete objects is therefore less accurate than in vector systems because "points" possess the area of an entire cell, and diagonal lines and area boundaries appear to have jagged "stair-step" edges inherent to the cell structure of rasters.

Vector GIS

Vector GIS possess data structures and display formats that parallel the three discrete cartographic types. *Point* vectors are defined by single points associated with spatial coordinates. *Line* vectors and *area* vectors include inferred line segments between a series of coordinate points. In the latter, line segments circumscribe areas to form polygons. Modern GIS employ an "arc-node" data structure for spatially representing the area data type. Arcs include a sequence of coordinates and the assumed lines between them that form a border between two adjacent polygons (or a map edge). Nodes are the end-points of arcs that occur where three or more polygons meet. All vector objects are linked to records in a data table that can include many attributes. For instance, an area vector that portrays the extent of a specific soil type might be linked to a data table that gives its classification, pH, texture, fractions of sand, silt, clay, organic matter, and the like. Most GIS provide a digitizing function that permits tracing of point, line, or area features on-screen to generate corresponding vector data. Vector GIS can be spatially accurate and precise because the positions of objects are controlled by the coordinates of the points which define them, and modern surveying methods ensure both. Vector GIS are required whenever accurate locations, area, or perimeter data are necessary (e.g., in portraying property boundaries).

Continuously varying information, such as elevation data, are generally represented by isoline contours in vector GIS. Alternatively, triangulated irregular network (TIN) models permit surfaces to be described by numerous triangular facets, where each corner or node represents a measurement in the continuous field. Unlike the common cell size of rasters, TIN models are variable in resolution, which means that regions with little change may be covered by larger triangles, while many small triangles can represent the greater detail necessary in areas showing more surface complexity.

The dominant application of vector GIS lies in working with spatial databases. Municipalities manage properties, power lines, and basic infrastructure, while archaeologists manage archaeological sites in regions or artifacts within individual sites (e.g., see Conolly and Lake, 2006). Regional databases are managed by vector systems because such discrete objects as "sites" or "artifacts" are best described by points, lines, or areas. Database queries can be bidirectional – made by pointing to elements on a display screen or through *structured query language* (SQL), a standard set of rules for asking such questions of databases as "Sites = Archaic" (which will select and display only the locations of Archaic sites). Selected elements may be simultaneously displayed in map and tabular form, yielding complete information that includes spatial relationships seen graphically.

Fundamental operations and tools

The GIS toolbox offers a wide variety of operations that may be performed with functionality varying between vector and raster systems. Their real power occurs in their combination, when several are chained together to achieve complex results.

Map reclassification

Reclassification is one of the most widely employed of all GIS operations. It permits generalization of a map from many to fewer categories and might be employed to reduce several hundred soil types to three that indicate relative suitability for maize agriculture, for example.

Distances and buffering

The spatial character of GIS permits proximities and distances to be computed. With discrete vector objects, a fixed distance defines a zone known as a *buffer*, represented by an area vector. An example might be a 500 m exclusion zone around a sensitive riparian habitat. Raster GIS permit continuous distance surfaces to be generated where each cell holds a distance to the nearest target cell of interest (e.g., a water source). Distances might be linear or a "cost-distance" based on premises about difficulty of movement considering slope, elevation changes, and land cover types.

Boolean operations and models

Boolean algebra utilizes variables that assume only two values (typically 0 or 1, or false and true). The Boolean intersection compares two or more binary GIS layers: if A represents proximity to water and B good soils, then their intersection represents those locations where both conditions are true. For a true result under a Boolean union, only one of the inputs must be true, however. Boolean methods form a fundamental tool for constructing simple yet powerful models based on a potentially large number of relevant inputs.

Map algebra

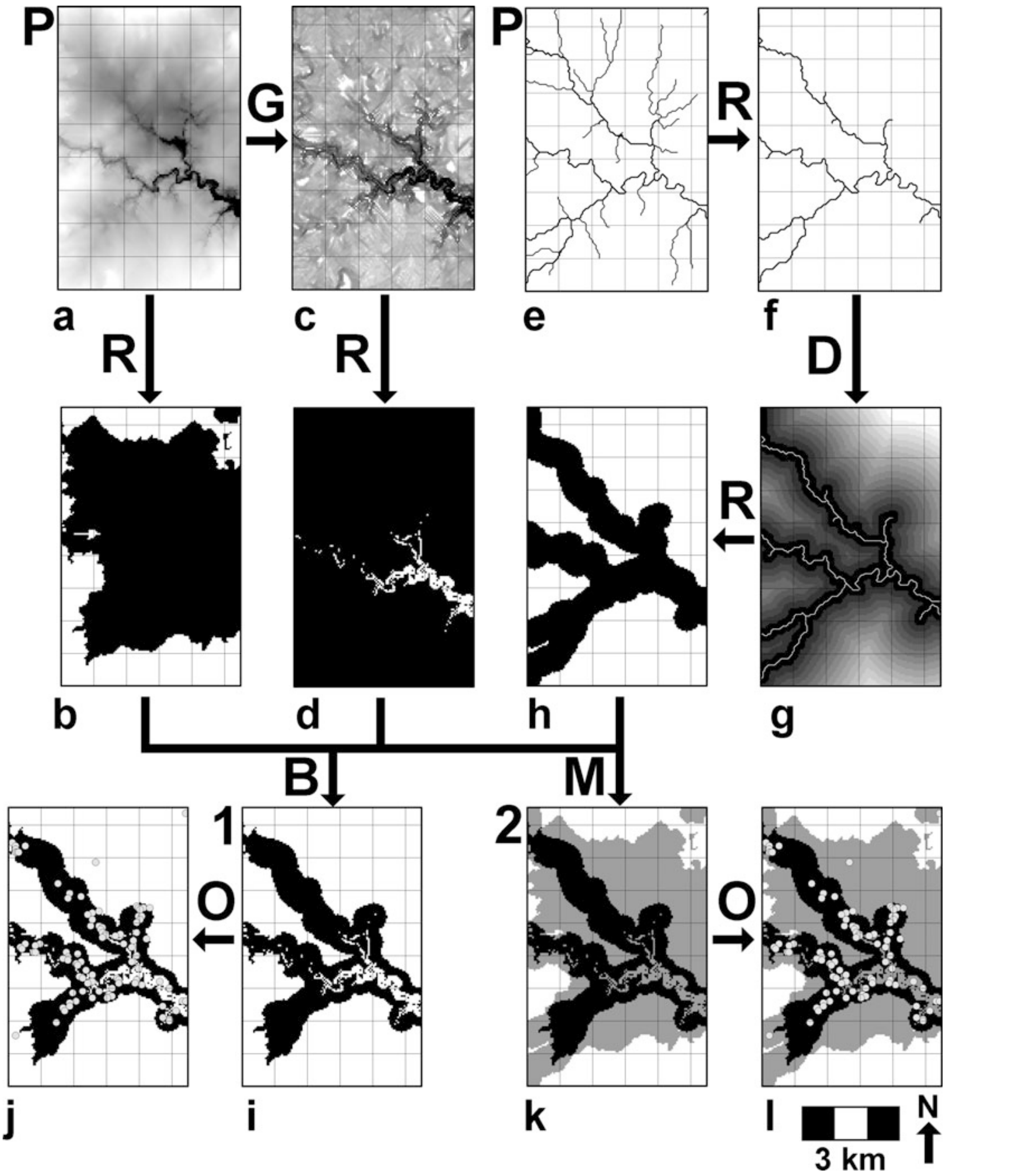
The application of mathematical operations to layers is uniquely a raster technique and one of the most powerful tools in GIS because it permits the development and application of complex mathematical and statistical models. Operations include addition, subtraction, multiplication, division, square roots, logarithms, the finding of minima and maxima, and the computation of means. Map algebra can be thought of as a mathematical function applied locally on a cell-by-cell basis where

$$\text{newlayer} = f(\text{oldlayer}_1, \text{oldlayer}_2, \ldots, \text{oldlayer}_k)$$

for a k multilayer operation (where f represents a mathematical function).

Neighborhood and zonal operations

While map algebra manipulates raster data in a single cell vertically through multiple layers, neighborhood operations function in a single layer by evaluating cells in a neighborhood of varying sizes or shapes around each cell, returning, for example, the minimum, maximum, or average of neighborhood values. Many of these operations amount to filters that are employed in terrain or image processing.



Geographical Information Systems (GIS), Figure 1 GIS operations in the context of building archaeological location models based on the premise that archaeological sites tend to occur at low elevations, on level ground, and close to secure water. In (**a**), the primary (*P*) layer, a DEM, is subjected to a reclassification (*R*) operation to yield a Boolean (true-false or 0–1) layer showing (**b**), *low elevation*, based on a threshold value. A gradient (*G*) operation is also applied to the DEM to yield (**c**), a *slope* layer, which in turn is reclassified to indicate (**d**) *level ground*, also Boolean. The primary layer (**e**), *water*, is reclassified to indicate (**f**), *permanent water*, which is used as input to a distance operation (*D*) to yield (**g**), *linear distance to permanent water*, and reclassified for (**h**), a Boolean indication of *proximity to permanent water*. *Model 1* (**i**) is formed by the Boolean intersection (*B*) of b, d, and h, and its performance is evaluated through an overlay (*O*) of (**j**) containing *known archaeological sites*, which registers as 86 % correct in a model encompassing 29 % of the region. *Model 2* (**k**) arises through the application of (*M*) map algebra to compute the sum of **b**, **d**, and **h**, where higher sums indicate locations that meet a greater number of the specified conditions. The overlay of (**l**), *known archaeological sites*, shows that all occur in the two highest categories, which encompass 75 % of the area, while results for the highest category are identical to the Boolean model.

Related are zonal operations that evaluate data in one layer within a zone defined by another, such as average income among households (layer 1) within a county (layer 2).

DEM creation and processing

With the prominence of landform variables in many archaeological applications, most GIS include interpolation tools, including geostatistical routines, for generating DEM (digital elevation models) from point or contoured elevation data. Additionally, numerous tools generate specific terrain characteristics making use of neighborhood operations. *Shaded relief* illuminates a terrain surface to mimic the effects of a light source shining on an actual surface, with bright areas and cast shadows. *Slope* is simply the first derivative or gradient which quantifies steepness, while *aspect* defines the azimuth or direction of maximum slope. *Drainage lines* may be derived analytically by modeling water flow as it runs through dropping elevations, and *ridge lines* can be obtained by reversing the algorithm. Watersheds may be generated by defining a drainage system and all points that flow into it. *Intervisibility* between two points involves computing a ray between them and determining whether intervening terrain is of sufficient elevation to block it. A *viewshed* refers to all locations visible from a point or points. Much of the terrain functionality originally developed in raster GIS can now also be performed on TIN models in the vector domain.

Image processing

Image processing modules exist within raster GIS for the manipulation and enhancement of imagery, whether from satellite, aerial, or terrestrial sources. These tools utilize neighborhood operations to perform such tasks as low-pass filtering to reduce noise, high-pass filtering to eliminate trends, and edge detection to isolate and enhance discrete boundaries. Brightness and contrast changes can improve visualization, and a variety of image classification methods permit identification of naturally similar regions.

Statistical operations

Some GIS offer a limited suite of descriptive statistics, conventional inferential and spatial statistical tests (such as tests for autocorrelation), and multivariate procedures for spatial modeling.

Network analysis

A network, such as a road lattice or a dendritic drainage system, is typically represented by line vectors. Each arc in the network can indicate impedances to flow or movement. Network analysis is useful to fire departments, emergency services, or traffic controllers because it permits optimum travel times and routes to be computed through complex networks by considering such variables as distances, typical velocities, traffic, and other relevant factors.

Several fundamental GIS operations are illustrated in Figure 1 where their utility for problem solving is demonstrated in the context of archaeological location modeling.

Summary

GIS are all-purpose software for handling and processing spatially distributed information. Because archaeological data are inherently spatial, GIS have had great impact on the discipline as general data management tools for regional and within-site databases, for analyzing past routes of travel, defining site catchments, understanding resource distributions, examining social landscapes based on mutual intervisibility, analyzing settlement choices with respect to environmental conditions, and for developing models of archaeological location.

Bibliography

Allen, K. M. S., Green, S. W., and Zubrow, E. B. W. (eds.), 1990. *Interpreting Space: GIS and Archaeology*. London: Taylor and Francis.

Conolly, J., and Lake, M., 2006. *Geographical Information Systems in Archaeology*. Cambridge: Cambridge University Press.

Gaffney, V. L., and Stančič, Z., 1991. *GIS Approaches to Regional Analysis: A Case Study of the Island of Hvar*. Ljubljana: Znanstveni Inštitut, Filozofske Fakultete.

Kohler, T. A., and van der Leeuw, S. E. (eds.), 2007. *The Model-Based Archaeology of Socionatural Systems*. Santa Fe: School for Advanced Research.

Kvamme, K. L., 1989. Geographic information systems in regional archaeological research and data management. In Schiffer, M. B. (ed.), *Archaeological Method and Theory*. Tucson: University of Arizona Press, Vol. 1, pp. 139–202.

Lock, G. R., and Stančič, Z. (eds.), 1995. *Archaeology and Geographical Information Systems: A European Perspective*. London: Taylor and Francis.

Madry, S. L. H., and Rakos, L., 1996. Line-of-sight and cost-surface techniques for regional research in the Arroux River valley. In Maschner, H. D. G. (ed.), *New Methods, Old Problems: Geographic Information Systems in Modern Archaeological Research*. Carbondale: Center for Archaeological Investigations/Southern Illinois University, pp. 104–126.

McCoy, M. D., and Ladefoged, T. N., 2009. New developments in the use of spatial technology in archaeology. *Journal of Archaeological Research*, **17**(3), 263–295.

Mehrer, M. W., and Wescott, K. L. (eds.), 2005. *GIS and Archaeological Site Location Modeling*. Boca Raton: CRC/Taylor and Francis.

Wheatley, D., 1995. Cumulative viewshed analysis: a GIS-based method for investigating intervisibility, and its archaeological application. In Lock, G. R., and Stančič, Z. (eds.), *Archaeology and Geographical Information Systems: A European Perspective*. London: Taylor and Francis, pp. 171–186.

Wheatley, D., and Gillings, M., 2002. *Spatial Technology and Archaeology: The Archaeological Applications of GIS*. London: Taylor and Francis.

Cross-references

Data Visualization
Landscape Archaeology
Remote Sensing in Archaeology

GEOMORPHOLOGY

Carlos E. Cordova
Department of Geography, Oklahoma State University, Stillwater, OK, USA

Synonyms

Evolution of the landscape; Landform study

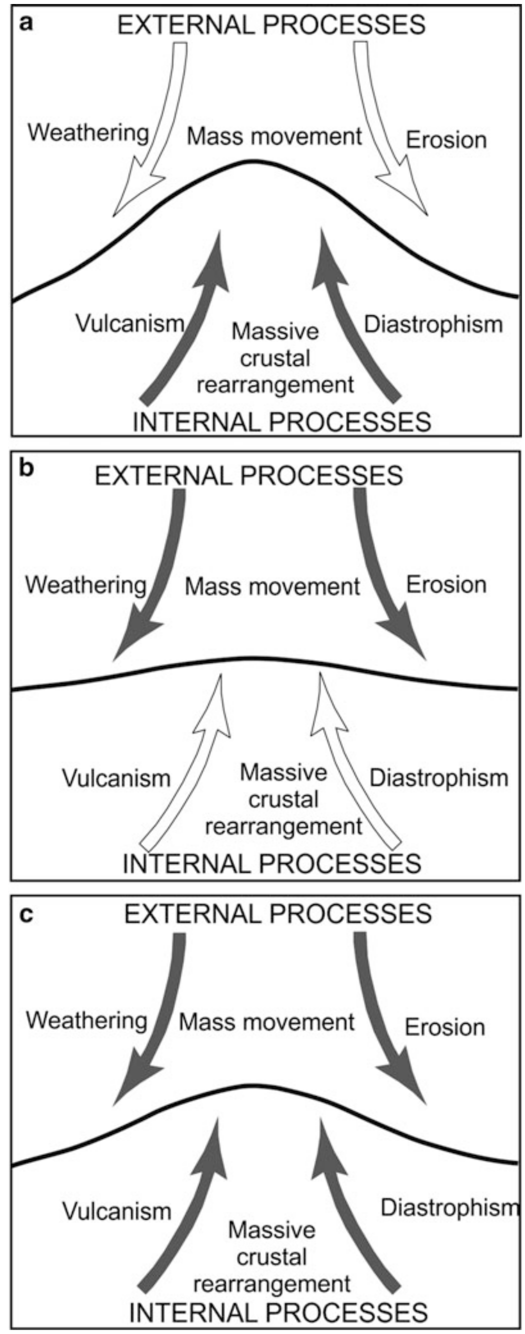
Definition

Geomorphology is the systematic study of landforms and the processes that form and change them.

Introduction

Geomorphology and its close ally, soil science, are major components of geoarchaeological practice today, and they were significant contributors to the emergence of the field of geoarchaeology. As the study of landforms, geomorphology helps to explain the evolution of the physical landscape, often referred to as "relief." Landforms are the result of physical forces referred to as geomorphic processes, and these processes are broadly divided into internal (endogenic) and external (exogenic) (Figure 1). The internal processes include movements of the earth's crust that build surface relief by means of diastrophism (folding and faulting of rocks) and volcanism. The external processes, on the other hand, are those that sculpt the landscape through weathering, mass movement, and fluvial, eolian, glacial, and coastal processes. When internal forces predominate (indicated by dark arrows in Figure 1a), the land surface is dominated by high elevations. In contrast, where there is little or no uplifting by internal forces, the land surface is eroded so as to form low relief (Figure 1b). Over long periods of time, most continental landscapes are normally the result of a balance between both forces (Figure 1c).

Explaining the relationship between generative processes and resulting landforms has been one of the main objectives of geomorphology. It is a complicated task because the landscape (i.e., the relief) is often created by a combination of processes acting at various intensities at different times and over varying durations. For this reason, geomorphologists have proposed different conceptual themes to analyze the origin of landscapes. William Thornbury enounced ten basic concepts in the early 1950s (Thornbury, 1969, 16–33). Concept 1 was borrowed from the theory of uniformitarianism: "the same physical processes and laws that operate today operated throughout geologic time, although not necessarily with the same intensity as now." Concept 2 states that "geologic structure is a dominant control factor in the evolution of landforms and is reflected in them," which alludes to the influence of geology in the shaping of landforms. Concept 6 proposes that "complexity of geomorphic evolution is more common than simplicity," as a reference to the ideas of polygenesis and inheritance, which state that (1) multiple processes acting at the same time or at certain times produce complex suites of landforms, and (2) current landforms bear shapes that are sometimes inherited from climates or environments of the past (Bauer, 2004). Emphasis on the influence of climate is expressed in



Geomorphology, Figure 1 Internal tectonic versus external climatic forces: landscape is affected by the dominance of internal forces (**a**) and external forces (**b**), and, over time, both forces tend to be in balance (**c**). Based on Hess and Tasa (2011) with modifications.

Geomorphology, Table 1 Time scales of geologic (geomorphic) events. A localized landslip or flow would be considered a mega-event if it occurred during a single day (such as a massive mudslide) but only a micro-event if it took 10 years for the material to be fully displaced (After Schumm 1991)

Relative magnitude of event	Time scale							
	1 day	1 year	10 years	10^2 years	10^3 years	10^5 years	10^6 years	10^8 years
Mega-event	Local soil slip or flow	Gully	Meander cutoff	Volcanic eruption	Terrace formation	Continental glaciation	Major folding, faulting	Mountain building
Meso-event	Rill	Local soil slip or flow	Gully	Meander cutoff	Volcanic eruption	Terrace formation	Continental glaciations	Major folding, faulting
Micro-event	Sand grain movement	Rill	Local soil slip or flow	Gully	Meander cutoff	Volcanic eruption	Terrace formation	Continental glaciation
Nonevent[a]	–	Sand grain movement	Rill	Local soil slip or flow	Gully	Meander cutoff	Volcanic eruption	Terrace formation

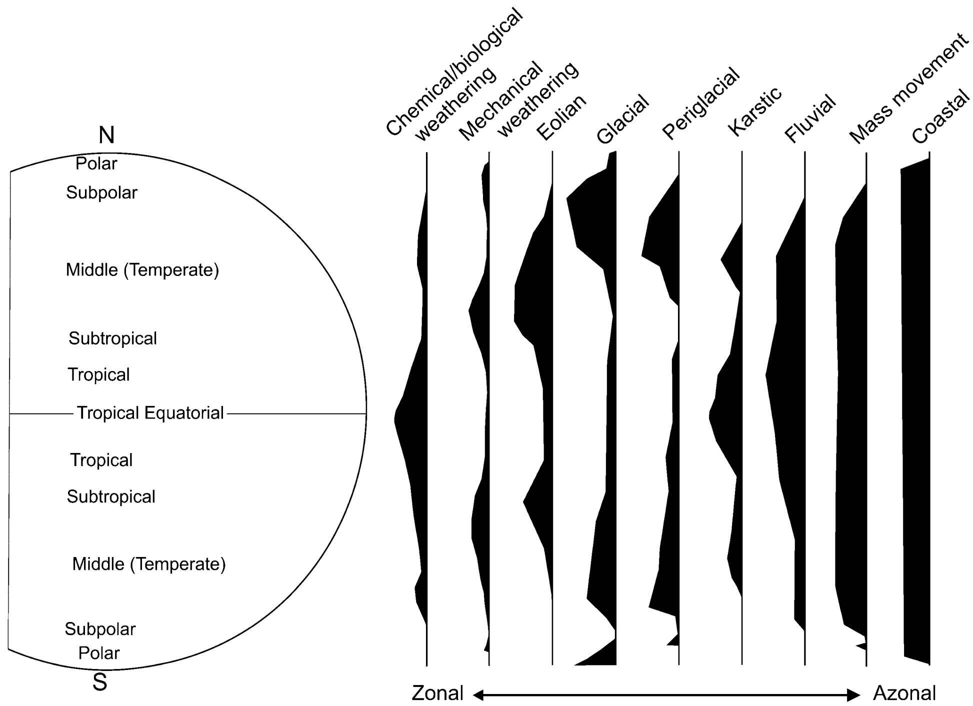
[a]A nonevent is explained in Schumm (1991, 34): "A mega-event during a short period may become a nonevent over longer time spans, as its effects are obliterated"

Concept 9 as "an appreciation of world climates is necessary for a proper understanding of the varying importance of the different geomorphic processes." The importance of Pleistocene climates in shaping modern relief is also emphasized in Concept 8 as "a proper interpretation of present-day landscapes is impossible without a full appreciation of the manifold influences and climatic changes during the Pleistocene," as well as Concept 7, which states "little of the earth's topography is older than Tertiary and most of it no older than Pleistocene." The fact that most of the landforms we see today were created during the Pleistocene – that is to say between ca. 1.8 million years and 10,000 years ago – suggests that we are looking at a relatively young landscape. Although recently superseded by new theoretical and empirical research, these concepts encapsulate the idea that process-landform is highly complex in the context of different lithologies, geological structures, tectonic movements, and climates.

The complexity of landform development derives primarily from the time scales and magnitudes at which geomorphic processes occur (Table 1). Processes of continental magnitude occur over longer periods of time than those affecting a particular landform, such as a dune or a point bar in a stream, which can change in a matter of days. The two main approaches to studying landforms, dynamic and historical geomorphologies, reflect the differences in time scales and magnitude of varied research goals. *Dynamic geomorphology* is the study of ongoing processes that requires observation and measurement of actual phenomena, while *historical geomorphology* is the study of long-term landform development that relies upon study of the evidence left behind by successive landscape changes. The two approaches benefit from each other because, for example, geomorphologists studying paleofloods based on the geologic record of fluvial deposits often draw their interpretations from studies of modern flood dynamics.

Time and magnitude are not the only subdivisions of geomorphology, as nearly every geomorphology treatise or textbook acknowledges other geomorphological approaches. Yet, opinions on how many range from unity (e.g., Butzer, 1976; Bloom, 1998) to the liberal idea that there are several geomorphologies (e.g., Thorn, 1988). Thus, in addition to the structural-climatic and dynamic-historical dualities, more elaborate subdivisions of geomorphology have been made. One of the most significant subdivisions in geomorphology is that between the structural and climatic approaches, which were emphasized during the middle decades of the twentieth century. Structural geomorphology (often referred to as tectonic geomorphology) is allied closely with the field of geology, where the interest lies in longer periods of time and a focus on internal processes. In contrast, climatic geomorphology has a stronger grounding in geography and emphasizes the effects of external processes.

The link between geomorphology and climate is based on the concept of a zonal distribution of landforms and processes, that is, the general – but not universal – distribution of geomorphic phenomena within global latitudinal belts. In geomorphology, therefore, a zonal distribution suggests that certain landforms and processes predominate at certain latitudes (Figure 2). Eolian environments, for example, tend to be predominant in the world's deserts, which are mostly found along the subtropical latitude high pressure belts. However, eolian environments, and particularly sand dune formation, exist at many latitudes and occur frequently along coasts where the supply of sand is substantial. In some cases, they may be found at middle latitudes, particularly in the cold deserts (e.g., the Gobi Desert in Eurasia and the Great Basin Desert in North America), and even in subpolar latitudes, where fluvioglacial activity also produces large amounts of sand. Likewise, glacial and periglacial phenomena are more typical of subpolar latitudes but are widely found atop mountain chains in all latitudes (and would be more common at high elevations today in the absence of global warming). Karstic environments, in which caves form by dissolution, are widely distributed over the continents, but they

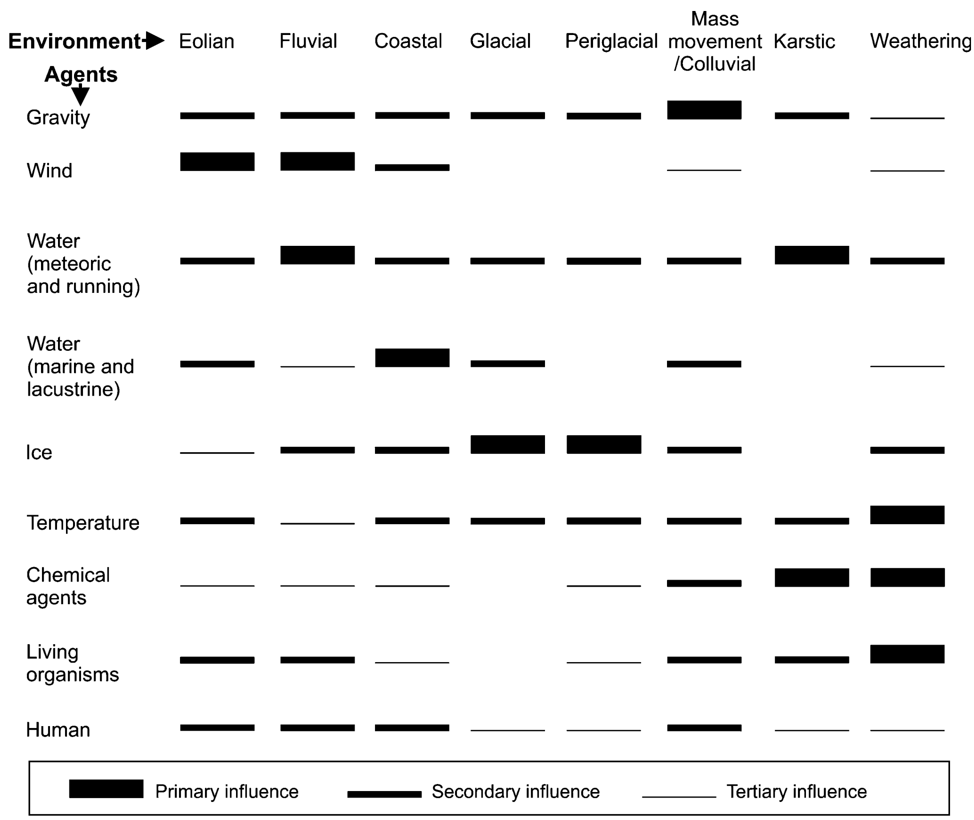


Geomorphology, Figure 2 Latitudinal distribution of main external geomorphic environments. Blackened areas on the vertical frequency scales for each environment show in which zones they are most influential.

actively occur only when water flows in abundance, particularly in tropical and middle latitudes. Finally, coastal (both marine and lacustrine) and fluvial environments are common throughout all latitudes regardless of climate types, and thus they are azonal. Their distribution and abundance vary in relation to areas where landmasses interface with bodies of water. Most processes that are not related to ice, however, are absent on and around the poles.

Sediments are the result of cumulative geomorphic processes resulting from erosion, transport, and deposition that, over time, form the sedimentary sequences that allow geomorphologists to determine the geomorphic environments of deposition at a specific location for the duration of the depositional interval. Each geomorphic environment was characterized by particular depositional systems, some of which were related to a specific process or agency or a combination thereof (Figure 3). In the case of eolian environments, the dominant processes are related to wind; with fluvial environments, it is meteoric/running water and wind; with glacial environments, it is the power of ice. In each environment, however, more than one agency is usually responsible for the development of a particular depositional system. For example, although wind is the most important agent in eolian deposition, there is also a smaller affect by gravity, water, temperature, etc. Additionally, the sand or silt being blown about has often been made available by previous fluvial or glacial processes, so that other environments may also be influential. This means that there are no sharp boundaries between environments, not spatially (as other contributor processes may be occurring nearby) and not temporally (as ancient processes that took place in the same locality can affect modern landforms). One can point to further complexities: the floodplain environment in a desert may contain facies produced by fluvial deposition, the sediments of which can be further entrained by eolian processes. Likewise, cave and rock-shelter formation is linked to the combination of two processes: dissolution and mass movement (collapse by gravity). It is important to note that humans are also geomorphic agents via their deliberate modifications of geomorphic systems through the construction of dams, canals, levees, and other features, as well as indirect destabilization of systems, such as lowering of the water table through pumping, which in turn may cause river channel entrenchment.

The properties of sediment (e.g., grain size, grain shape, bedding structure, mineral composition, etc.) are important for identifying the depositional environment. In turn, sediments contain within their characteristic features proxy data useful for other analyses. These may include charcoal for radiocarbon dating, magnetic properties for paleomagnetic dating, and microfossils for paleoenvironmental reconstruction as well as dating. Therefore, the work of geomorphology in determining the properties and origin of the sediment in a stratigraphic sequence is crucial for many different questions.

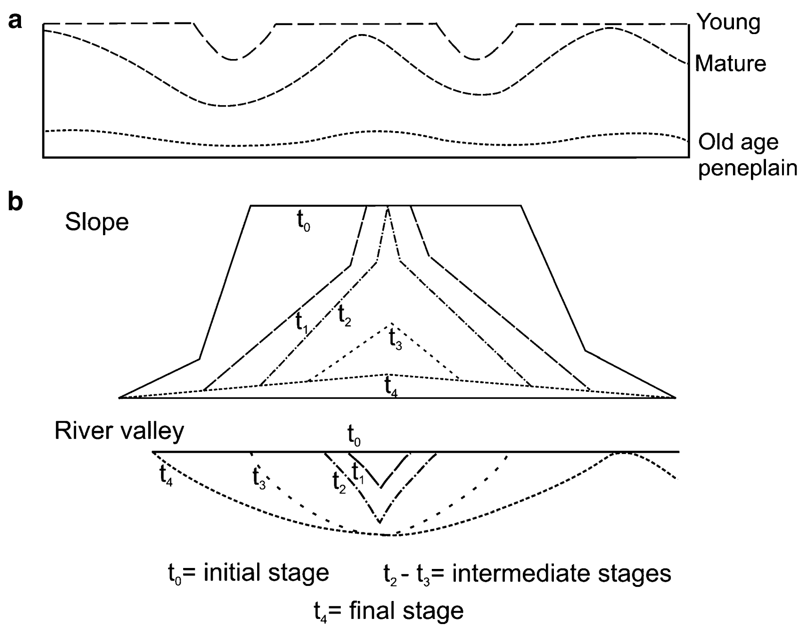


Geomorphology, Figure 3 Geomorphic agents that define each geomorphic environment. The relative influence of each agent on each environment is portrayed by line thickness as indicated in the key at the bottom of the diagram: primary means that this agent is the unique or fundamental agent in the environment; secondary means that the agent is important in the environment but not fundamental; and tertiary means that the agent occurs in the environment but is neither important nor fundamental.

History and evolution of geomorphology

Landforms and their origin have been subjects of scientific interest for several centuries. Geologists, naturalists, science enthusiasts, and even travelers have been intrigued by the formation of landscape features. The ideas of catastrophism by Georges Cuvier (1769–1832) and uniformitarianism by James Hutton (1726–1797) implied opposing modes of change, as both attempted to explain the formation of the landscape in different ways. Many lesser known geomorphologists lived and worked in Europe during the seventeenth and eighteenth centuries, and early practitioners of geomorphology numbered among the geologists of the eighteenth century (Davies, 1989). But it was not until the end of the nineteenth century when geomorphology took shape as a discipline (Goudie, 2011). In North America, the work of John Wesley Powell (1834–1902) and Grove Karl Gilbert (1843–1918), both of whom studied landforms in the western United States, provided the basis for a modern geomorphology, particularly through the introduction of new ideas. For example, in 1875, Powell introduced the concept of base level, by which he meant the level to which all rivers erode (i.e., the sea level), a concept that is still in use. Similarly, in other parts of the world, other scientists left an imprint in geomorphology that persisted through the following centuries. One is the case of the Swiss paleontologist Louis Agassiz (1807–1873), who established the basis for studying and interpreting glacial environments, including the vestiges left by past ice ages.

The American William Morris Davis (1850–1934) and the German Walther Penck (1888–1923) are often seen as the founders of modern geomorphology. Each of these geologists developed synthetic models of landscape evolution, which, despite criticism, became the basis for landform interpretation by geomorphologists in the first half of the twentieth century. The geographic cycle proposed by Davis (1899) considered the vertical downwearing of the landscape by erosion from which young, mature, and old landscapes could be identified (Figure 4a). Yet, the uplifting of an old landscape would mean rejuvenation and initiation of a new cycle. In contrast, Penck's (1924) model considered erosion acting laterally so as to create parallel slope retreat and parallel valley widening



Geomorphology, Figure 4 Abstract representation of models of erosion and landscape evolution by W. M. Davis (1899) (**a**: *top*) and W. Penck (1924) (**b**: *bottom*).

(Figure 4b). These models of landscape evolution were soon replaced by explanations based on field data.

Because certain processes occur mainly at specific latitudes or climatic zones, the term climatic geomorphology was popularized particularly by French and German schools in the early twentieth century (Goudie, 2011). The field has grown to the point that, in addition to glacial, periglacial, and desert landscapes, sometimes references are made to tropical landscapes and even more specific environments such as savanna and Mediterranean geomorphology (Butzer, 1976). An alternative to the climatic approach is a structural approach, which has been developed to emphasize not only the effect of tectonic structure but also broader aspects of continental and even planetary scale. The theory of plate tectonics energized the development of structural geomorphology from the mid-twentieth century. Although this focus was developed in many countries, it characterized most of the geomorphological studies in the former Soviet Union, a trend that made sense given the size of their territory (Walker and Grabau, 1993). Throughout the world, however, the climatic and structural views drew heavily from the disciplines of geography and geology/geophysics, respectively.

By the 1970s, geomorphology around the world was developing nationalistic styles, sometimes based on each country's territorial characteristics, economic trends, and even academic policies (Walker and Grabau, 1993). This led to the creation of different models, standards, terminology, and approaches. But over the years since then, geomorphologists have come to realize that global collaboration, understanding, and standardization are important. Unification of geomorphological thoughts and efforts materialized with the creation of the International Association of Geomorphologists (IAG), under whose auspices the first international conference in geomorphology was held in Manchester in 1985. It was not until 1989, during the second geomorphological conference meeting in Frankfurt, that the association was formally created. Subsequent meetings took place every 4 years in Hamilton, Canada (1993); Bologna, Italy (1997); Tokyo, Japan (2001); Zaragoza, Spain (2005); Melbourne, Australia (2009); and Paris, France (2013). Regional meetings, some sponsored by the IAG and/or national and regional organizations, are also taking place around the world. Additionally, small specialized sections in the European Geological Union, the International Geographical Union, the Association of American Geographers, the Geological Society of America, and the Society for American Archaeology have sponsored geomorphology-related sessions during their annual meetings.

Almost three decades before the creation of the IAG, the Binghamton Geomorphology Symposium had laid a foundation for discussion of theoretical and technical matters in geomorphology. The first symposium was conducted under the direction of Marie Morisawa and Donald Coates of the State University of New York (SUNY) at Binghamton in 1970. Symposia were organized every year afterwards. Although first attended primarily by American and Canadian geomorphologists, the event has gradually attracted participants from all continents. The published proceedings of the symposia have become important sources of information on the theoretical and technological advances of geomorphology.

Some have become keystone publications in geomorphology, for example, *The Scientific Nature of Geomorphology*, edited by B. L. Rhoads and C. E. Thorn (1996). Although individual proceedings volumes exist, in recent years, the Elsevier journal *Geomorphology* publishes the proceedings. The Binghamton Symposia are organized around a specific subject. Some examples of symposia topics include Quantitative Geomorphology (1971), Geomorphology of Arid Regions (1977), Space and Time in Geomorphology (1981), Soils and Landscape Evolution (1991), Biogeomorphology (1995), Geomorphology and Ecosystems (2005), Complexity in Geomorphology (2007), and Geospatial Technologies and Mapping in Geomorphology (2010).

Geomorphology has been subdivided into several areas of topical specialization. Currently, the most common specialization subdivisions in the United States are fluvial geomorphology, eolian and coastal geomorphology, weathering geomorphology, mass movement, periglacial and glacial geomorphology, Quaternary geomorphology, biogeomorphology, environmental geomorphology, geoarchaeology, and planetary geomorphology (Butler, 2003). Advances in information technology have also had an impact. The development of GIS (geographic information systems), DEMs (digital elevation models), and software with statistical capabilities has been crucial to the development of geomorphic models, and these have supplanted many of the old approaches, since a single model can incorporate information on climate, structure, soil, vegetation, and even different time scales, as well as quantitative and qualitative aspects of landform development.

Aided by computerized cartography and animation, modeling has had a great impact on the discipline. It has also been important for mapping the evolution of slopes under erosive forces, which in turn has provided important elements for geomorphic hazard mapping. Three- and four-dimensional models have become important in the reconstruction of ancient river systems, even in areas now below sea level (Brown, 2008). In many instances, four-dimensional models incorporating time have been useful for explaining landscape evolution in the classroom. Thus, modeling in geomorphology has essentially become the bridge between theory and practice, past and present, reality and abstraction, and pure and applied research.

A positive surge in geomorphological research resulted from advances in chronometric dating techniques. This derived not only from the increased accuracy achieved through accelerator mass spectrometry (AMS) radiocarbon dating but also from the application of several other methods, particularly luminescence dating. Although the latter is mainly applied to eolian environments, where carbon for AMS dating is often scarce or unavailable, the technique is being extended to other environments, particularly coastal and fluvial. In volcanic geomorphology, K-Ar and Ar-Ar have been of great value for dating periods deeper in time. Advances in the use of other isotopic methods such as uranium series and cosmogenic nuclides (e.g., ^{10}Be, ^{25}Al, ^{36}Cl) are making a strong impact on the geomorphology of the twenty-first century. The use of tracers in geomorphology has helped in tracking and modeling movements of water, wind, and sediments. Tracers can be passive (e.g., painting, exotic minerals or particles, fluorescent, magnetic, and radioactive materials) or active (e.g., radio transmitters) (Hassan and Ergenzinger, 2003). Beyond fluvial geomorphology, tracers can include atmospheric and hydrological tracers and those tracers used for monitoring soil erosion and hillslope processes (Foster, 2000). More recently, GPS technologies have added more accurate ways of tracing geomorphic processes (Stockdale et al., 2008). Advances in remote sensing and mapping have also been influential in the development of geomorphology earlier in the present century.

Currently, there are no geomorphology departments or academic units in universities. Normally, geomorphology is a specialization within geology, geosciences, or geography departments. It figures as a mandatory course in the curricula of geologists, geophysicists, and geographers and in some colleges among the courses required for archaeologists. Specialists in geomorphology are often employed in a variety of jobs ranging from state and national geological surveys to private consulting firms, oil companies, environmental assessment, contract archaeology, and very commonly in academic centers of higher education for teaching and research.

Theoretical aspects

Interest in concepts and models has existed among practitioners of geomorphology throughout the history of the discipline. Conceptual models that explain the origin of landforms were popularized first by the works of William M. Davis and Walther Penck (see "History and Evolution of Geomorphology" section, Figure 4). Theoretical interest is also seen in the creation of conceptual themes proposed by W. Thornbury (see "Introduction" section). But in the second half of the twentieth century, the so-called theoretical geomorphology was enriched by the new scientific paradigms that appeared during the 1960s and 1970s in the realms of quantitative research and systems theory. This trend gave birth to many geomorphological models expressed in mathematical terms, i.e., in the form of equations and graphs. Theoretical research began appearing in journals and books in the 1970s, some of it as part of the proceedings of the Binghamton Symposia, as well as other venues sponsored by the IAG.

Richard Huggett (2007) wrote that geomorphological theory borrowed concepts from other disciplines, very often from physics, and in particular from thermodynamics. As a result, concepts such as equilibrium, stability and non-stability, complexity, and chaos are still ingrained in geomorphological modeling. The concept of geomorphological threshold is tied to equilibrium of the landscape and implies that a geomorphic system, say a fluvial stream, evolves from its original state and passes through different states of equilibrium and nonequilibrium; when the system crosses a threshold, however, its parameters change, and it is unable to return to its original state (Schumm, 1973, 1979). The concepts of threshold and landscape equilibrium encapsulate the idea of landscape sensitivity, which implies that streams and their valleys have the propensity to change, sometimes triggered by minor impulses (Brunsden, 1990). This understanding has formed a basis for explaining the responses of geomorphic systems to climatic change (Bull, 1991). Thus, threshold and equilibrium have developed into a process-response model that allows one to predict the behavior of geomorphic systems, e.g., in small streams and alluvial fans. A process-response model explains phases of equilibrium and threshold events in terms of four stages: (1) a reaction time (which is the lag time between the perturbation created by a weather event and the time a change in the system is observed), (2) the relaxation time (the time needed by the system to establish a new equilibrium or threshold condition after it has reacted to the perturbation), (3) the response time (the sum of the reaction time and the relaxation time), and (4) the persistence time (the time span of the new equilibrium condition after a stream has adjusted to a perturbation) (Bull, 1991).

The processes of stream equilibrium were worked out in several models by Stanley Schumm (1973, 1979, 1991), who further suggested different types of equilibria – static, steady, and dynamic – implying that equilibria occur over different time scales and that changes in the system do not necessarily imply a crossing of thresholds. The linearity of the threshold system has been challenged by the bifurcation and catastrophe models (Huggett, 2007). The catastrophe theory, which is a branch of the bifurcation model, suggests that streams have different bifurcation points. According to the model, in passing through a bifurcation point, the system loses its structural stability and undergoes a sudden or catastrophic change to a new form.

Complexity in geomorphic systems, derived from multiple processes acting simultaneously at different scales, is a theoretical aspect conceptualized in a series of principles (Huggett, 2007). In essence, the principles describe the chaotic nature of geomorphic systems, which are inherently unstable and self-organizing. Although it is chaotic, the dynamic stability of the systems does not occur randomly; in other words, the chaotic events occur in an orderly way. Additionally, the chaotic nature of the systems and their ability to self-organize vary with scale. In some situations, a system may look chaotic at a small scale, but non-chaotic at a larger scale.

Synergetic developments with other disciplines

The historical development of geomorphology has paralleled the development of other scientific disciplines that deal with landscape evolution. Beyond geography and geology, geomorphology has had close connections with hydrology and hydraulic engineering, from which it borrowed many concepts and models of hydraulic geometry (Knighton, 1984). Many geomorphologists in the United States work in projects related to the hydrological network of the country, particularly those related to flood control and hazards (Butler, 2003).

Geomorphology also evolved parallel to, and in frequent collaboration with, Quaternary science. In Europe and most of North America, Quaternary studies were initially focused on glacial morphology, but, during the second half of the twentieth century, attention turned steadily to non-glaciated areas. First, interest was directed toward loess deposits and, subsequently, to Quaternary changes in deserts and the tropics. Another aspect of Quaternary research where geomorphology has been deeply involved is that of sea-level change related to glacial-interglacial cycles. The cyclical locking up of global water in ice sheets and its subsequent release through melting caused fluctuations in sea level that affected the base level for the world's rivers. Lower sea level brought about a drop in base level, which triggered erosional downcutting within river valleys, and the following sea-level rise flooded the valleys and floodplains. Thus, glacial and interglacial phases led to changes well beyond the glacial systems themselves, especially in other systems affected by sea level as well as atmospheric circulation because the shifts in wind patterns during glacial stages extended outside the higher latitudes. For example, shifting atmospheric cell systems brought dryness to some areas, while eolian systems moved by the spreading ice sheets created characteristic landforms, such as stabilized sand dunes or loess plateaus. Quaternary science has particularly strong ties with climatic geomorphology and with historical geomorphology. Process geomorphology (dynamic geomorphology) is still important in the sense that many modern glacial processes observable in higher latitudes provide clues to the interpretation of numerous glacially related landforms in middle latitudes where they were left behind by Pleistocene glacial advances.

Recently, geomorphology has established ties with biogeography, hence creating biogeomorphology, which explores the role of plants in landform stability. Geomorphic stability has often been discussed, but the involvement of biological systems is a new addition to such concerns (Butler, 2003). Biogeomorphology was the topic of two Binghamton Symposia (in 1995 and 2009).

Geomorphologically stable surfaces permit soil formation processes to begin, and this important aspect of landscape evolution demonstrates the close connection of soil science to the growth of geomorphology. Paleosols (or geosols) are buried soils that once formed at the ground surface but were then covered by sediments. The presence of one or many stratified paleosols indicates not only the periods of landscape stability, but it also provides evidence for dating the soil and determining characteristics of the paleoenvironment at the time soil formation was ongoing. In the same way, the absence of soil formation in a sedimentary sequence can be indicative of landscape instability, perhaps caused by erosion or a rapidly changing environment. Presently, there are many practitioners within the subdiscipline of soil geomorphology, and numerous publications exist in the form of treatises (e.g., Daniels and Hammer, 1992; Gerrard, 1992; Birkeland, 1999) as well as shorter publications in journals such as *Geoderma*, *Catena*, and *Geomorphology.*

Geomorphology and geoarchaeology

Geomorphologists who engage geoarchaeological questions view archaeological sites as part of one or more geomorphic systems. Thus, geoarchaeological settings can be nested within other depositional settings or environments, which in turn form part of a greater geomorphic system (Table 2). In geoarchaeology, the most common among these settings are eolian (sand and loess), alluvial (i.e., fluvial), colluvial, littoral, and cave and rock-shelters. Less common worldwide, but frequent in certain regions, is the volcanic setting. Very uncommon but possible are geoarchaeological settings in glacial and periglacial environments.

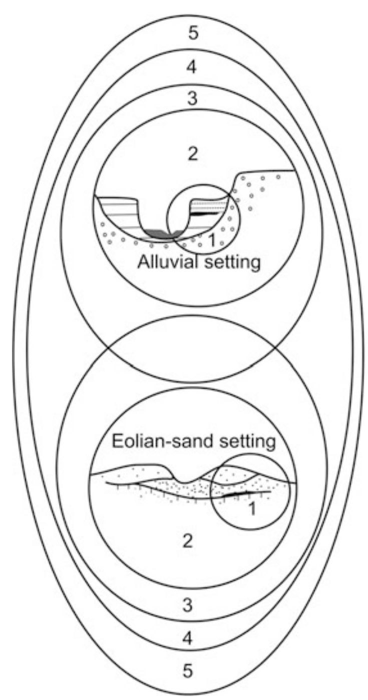
Geomorphology also provides evidence to reconstruct the paleoenvironment of an archaeological locality at different scales. Bruce Gladfelter (1977) exemplified these scalar relationships in a series of levels from as small as the depositional setting associated with a specific site to as large as the greater morphoclimatic system. But in a more modern version of this model, the geomorphological context of archaeological material can be conceptualized within at least five different levels: (1) the depositional setting associated with the archaeological material, in which the perspective of sedimentary facies becomes important; (2) the greater depositional/geomorphic environment (equivalent to the right column in Table 2); (3) the level of geomorphic system (left column in Table 2), which in turn represents a larger landscape/landform unit; (4) the greater regional system; and (5) the morphoclimatic level, which may or may not be directly associated with zonality.

Geomorphology, Table 2 Geomorphic environment and associated depositional environments

Geomorphic system	Depositional/geomorphic environments
Eolian	Sand and loess
Alluvial	Alluvial (overbank, channel, levee, deltaic facies)
Colluvial	Mass movement, overland flow, landslides, mudflows
Littoral	Beach, estuarine, deepwater, lagoonal, tidal
Volcanic	Lava and pyroclastic
Glacial[a]	Moraine, eskers, fluvioglacial, limnoglacial
Periglacial	Solifluction/gelifluction, polygons, pingos
Weathering	Deluvial, weathering crust, soils

[a]Archaeological sites are very rare, but possible, in active glacial environments

These levels of geomorphological analysis can be exemplified by two archaeological sites located in alluvial and eolian settings within the same region (Figure 5). At the first (lowest) level, evidence retrieved from sediments directly associated with the archaeological material is used in the analysis of the stratigraphy of the archaeological site itself. At the second level, evidence is retrieved from a larger area within the system, e.g., a segment of the river or a particular dune field, and the analyses conducted with this evidence are intended to understand the functioning of the fluvial or eolian system within the area immediately around the site. At the third level, evidence is retrieved in order to analyze the responses of the entire geomorphic system (the fluvial basin or sand sheet) with the goal of establishing correlations within each of the broader geomorphic alluvial and eolian systems and perhaps intersecting tectonic systems as well. At the fourth level, the analysis requires the correlation of data with those developed from a far broader region, wherein several fluvial basins and sand sheets may occur. At the fifth and highest level, correlations can be drawn to major global climatic trends, particularly using the evidence from deep-sea ocean and ice cap core records. The fact that the two settings (alluvial and eolian) in this example are located in the same region makes some of the analyses and correlations at higher levels (3, 4, and 5) inclusive, potentially demonstrating that geomorphic transformations at the two localities might have been responses to



Geomorphology, Figure 5 Geomorphological levels of analyses involving different scales around the geomorphic/depositional setting of an archaeological site.

the same climatic changes. In the case of the example in Figure 5, eolian sand destabilization may be correlative with stream incision due to a particular climatic factor of regional extent.

The above example uses an archaeological site (on-site research) as its point of reference. Although on-site geoarchaeology is the most common kind, particularly in the context of anthropological research, geoarchaeology is evolving to consider off-site research (Cordova, 2007). When it is conducted within the framework of geoarchaeological research, off-site geomorphological research avoids the potential biases created by site selection on the part of the excavator as well as the deliberate modification of the depositional system on the part of the ancient inhabitants. Sedimentological data removed only from within a site might misrepresent some process under study because the site might be in some way atypical of the regional environment surrounding it. The site might be located in a protected area, favored by peculiar conditions that were favorable for settlement. Certain evidence might be missing from the within-site record, thereby giving a false impression of the true patterning of geomorphic processes in the region beyond. Geomorphic settings might have been modified by the very act of establishing a human occupation, which might lead to misinterpretation. For example, dune invasion into an inhabited site may have been slowed or even halted by tree barriers and walls, thus hindering sand movement, an event that can mistakenly be taken as a natural process. In an alluvial setting, the accumulation of laminated sediments behind an artificial dam may give a false impression of a natural lake deposit. These two examples show how humans modify geomorphic systems by controlling geomorphic processes to some extent. One must not mistake the anthropogenically induced changes for natural ones. Doing so represents essentially sample error in that the evidence one collects is in fact unrepresentative of the area being studied.

Because geoarchaeology goes beyond the physical aspects of sediments to encompass biogeographic and cultural aspects (Butzer, 1982), geomorphological processes are often understood as being part of a more complex matrix of processes. Thus, the construction of a dam – a cultural structure – may create changes in the geomorphic system, which may then result in a change to the fluvial environment and its constituent facies. At the same time, the geomorphological analysis of the fluvial basin may provide information on the reason and purpose for the construction of the dam. On a broader spatial scale, the fluvial basin may not only be part of the climatic system but also part of a culturally produced architectural system, which may have further implications for the fluvial dynamics within the basin, as well as information bearing upon the reason for construction and failure of the dam.

Geomorphological modeling and technologies have also become part of geoarchaeological research. Remote sensing, in particular, has emerged as a prime tool in the mapping of features of large scale on the ground or features not clearly visible when in the field, such as the configuration of river meanders and scars. The evolution of the landscape is an important consideration in any archaeological research program, and it can be reconstructed or predicted using GIS and DEMs together with the typical ground-truthing inputs from empirical data obtained during geomorphological field exploration.

Summary

Geomorphology is the systematic study of surface processes that build and degrade landforms. In a broad sense, it encompasses the study of endogenic (internal) processes like volcanism and tectonism and exogenic (external) processes acting through the forces of weather and climate. Geomorphologists view these processes at different scales, from planetary through continental and down to a microscale. Processes involve different time scales as well: processes such as mountain building often take thousands to millions of years, while processes such as floods, landslides, earthquakes, and volcanic eruptions take hours or days. Climatic geomorphology has evolved into different areas, focusing on the main geomorphic/depositional environments: fluvial, eolian, colluvial, karstic, littoral, glacial, and periglacial. Geomorphology coevolved along with other developments in the fields of geology and geography. Geomorphology is finally a major component of geoarchaeological research, much of which has concerned the study of depositional and erosional settings associated with archaeological sites, as well as the major regional context of a site's surroundings/catchment or site complexes.

Bibliography

Bauer, B. O., 2004. Geomorphology. In Goudie, A. S. (ed.), *Encyclopedia of Geomorphology*. London: Routledge, Vol. 1, pp. 428–435.

Birkeland, P. W., 1999. *Soils and Geomorphology*, 3rd edn. New York: Oxford University Press.

Bloom, A. L., 1998. *Geomorphology. A Systematic Analysis of Late Cenozoic Landforms*, 3rd edn. Upper Saddle River: Prentice Hall.

Brown, A. G., 2008. Geoarchaeology, the four dimensional (4D) fluvial matrix and climatic causality. *Geomorphology*, **101**(1–2), 278–297.

Brunsden, D., 1990. Tablets of stone: toward the ten commandments of geomorphology. *Zeitschrift fur Geomorphologie, N.F. Supplementband*, **79**, 1–37.

Bull, W. B., 1991. *Geomorphic Responses to Climatic Change*. New York: Oxford University Press.

Butler, D. R., 2003. Geomorphology. In Gaile, G. L., and Willmott, C. J. (eds.), *Geography in America at the Dawn of the 21st Century*. New York: Oxford University Press, pp. 56–71.

Butzer, K. W., 1976. *Geomorphology from the Earth*. New York: Harper and Row.

Butzer, K. W., 1982. *Archaeology as Human Ecology: Method and Theory for a Contextual Approach*. Cambridge: Cambridge University Press.

Cordova, C. E., 2007. *Millennial Landscape Change in Jordan: Geoarchaeology and Cultural Ecology*. Tucson: University of Arizona Press.

Daniels, R. B., and Hammer, R. D., 1992. *Soil Geomorphology*. New York: Wiley.
Davies, G. L. H., 1989. On the nature of geo-history, with reflections on the historiography of geomorphology. In Tinkler, K. J. (ed.), *History of Geomorphology, from Hutton to Hack*. Boston: Unwin Hyman. Binghamton Symposia in Geomorphology, Vol. 19, pp. 1–10.
Davis, W. M., 1899. The geographical cycle. *Geographical Journal*, **14**(5), 481–504.
Foster, I. D. L. (ed.), 2000. *Tracers in Geomorphology*. New York: Wiley.
Gerrard, J., 1992. *Soil Geomorphology: An Integration of Pedology and Geomorphology*. London: Chapman & Hall.
Gladfelter, B. G., 1977. Geoarchaeology: the geomorphologist and archaeology. *American Antiquity*, **42**(4), 519–538.
Goudie, A., 2011. Geomorphology: its early history. In Gregory, K. J., and Goudie, A. (eds.), *The SAGE Handbook of Geomorphology*. London: Sage Publications, pp. 23–36.
Hassan, M. A., and Ergenzinger, P., 2003. Use of tracers in fluvial geomorphology. In Kondolf, G. M., and Piégay, H. (eds.), *Tools in Fluvial Geomorphology*. Chichester: Wiley, pp. 397–423.
Hess, D., and Tasa, D., 2011. *McKnight's Physical Geography: A Landscape Appreciation*, 10th edn. Upper Saddle River: Pearson Prentice Hall.
Huggett, R., 2007. A history of the systems approach in geomorphology. *Géomorphologie: Relief, Processus, Environnment*, **2**(2007), 145–158.
Knighton, D., 1984. *Fluvial Forms and Processes*. London: Edward Arnold.
Penck, W. D., 1924. *Die Morphologische Analyse. Ein Kapitel der physikalischen Geologie*. Stuttgart: Engelhorn. Geographische Abhandlungen. Reihe 2, Heft 2.
Rhoads, B. L., and Thorn, C. E., 1996. *The Scientific Nature of Geomorphology: Proceedings of the 27th Binghamton Symposium in Geomorphology*. Chichester: Wiley.
Schumm, S. A., 1973. Geomorphic thresholds and complex response of drainage systems. In Morisawa, M. (ed.), *Fluvial Geomorphology: A Proceedings Volume of the Fourth Annual Geomorphology Symposia Series Held at Binghamton, New York, September 27–28, 1973*. Binghamton: New York State University Publications in Geomorphology. Binghamton Symposia in Geomorphology, Vol. 4, pp. 299–310.
Schumm, S. A., 1979. Geomorphic thresholds: the concept and its applications. *Transactions of the Institute of British Geographers*, **4**(4), 485–515.
Schumm, S. A., 1991. *To Interpret the Earth. Ten Ways to be Wrong*. Cambridge: Cambridge University Press.
Stockdale, R. J., McLelland, S. J., Middleton, R., and Coulthard, T. J., 2008. Measuring river velocities using GPS river flow tracers (GRiFTers). *Earth Surface Processes and Landforms*, **33**(8), 1315–1322.
Thorn, C. E., 1988. *Introduction to Theoretical Geomorphology*. Boston: Unwin Hyman.
Thornbury, W. D., 1969. *Principles of Geomorphology*, 2nd edn. New York: Wiley.
Walker, H. J., and Grabau, W., 1993. Introduction. In Walker, H. J., and Grabau, W. (eds.), *The Evolution of Geomorphology: A Nation-by-Nation Summary of Development*. Chichester: Wiley, pp. 1–18.

Cross-references

Cosmogenic Isotopic Dating
Eolian Settings: Loess
Eolian Settings: Sand
Mass Movement
Optically Stimulated Luminescence (OSL) Dating
Radiocarbon Dating
Sedimentology
Soil Geomorphology
Soil Stratigraphy

GEOPHYSICS

Apostolos Sarris
Laboratory of Geophysical-Satellite Remote Sensing and Archaeo-environment, Foundation for Research and Technology, Hellas (F.O.R.T.H.), Institute for Mediterranean Studies (I.M.S.), Rethymnon, Crete, Greece

Synonyms

Ground-based remote sensing

Definition

Geophysics. The science dealing with quantitative measurements of the physical properties, phenomena, and processes of the Earth.

Introduction

Geophysics is a branch of the remote sensing sciences that focuses on the study and measurement of the Earth's properties and processes. Applied, or exploration, geophysics (also called geophysical prospection) often involves measurements taken at the Earth's surface to infer changes in properties beneath the surface. Various techniques have been developed for carrying out such measurements, mainly to conduct medium- or high-depth investigations involving geological or resource exploration applications. Within the archaeological domain, these methods have been adapted in order to address questions related to the buried residues of past human activities (e.g., habitation, husbandry, workshop activity) and mainly for the detection of architectural remains.

Initially, geophysics as employed in archaeology was considered a subfield of archaeometry, but it gradually obtained its independence to form the field of archaeological prospection, of which the earliest examples emerged toward the middle of the twentieth century through the employment of aerial photography, soil resistance, and magnetic techniques (Clark, 1990; Scollar et al., 1990; Linford, 2006). Applications have been multiplied in the decades since then.

The success of the varied methods depends mainly on the contrast between the properties of the underground targets compared to those of the soil matrix that surrounds them. This is especially true when the subsurface contains increased levels of complicating noise due to recent anthropogenic activity or other shallow geologic processes. Target detection is thus a function of various parameters, including the dimensions and physical properties of the target, the depth of investigation, the degree of preservation of the remains, and the sampling interval.

Methodological approaches

Geophysical methods can be active (in which an energy source is required in the detection process) or passive (in which no energy is emitted from the device). Some of the major methods briefly summarized below are electrical resistivity, magnetometry, magnetic susceptibility, electromagnetic methods, ground-penetrating radar, seismic techniques, and gravimetry. Extended overviews of these methods can be found in Gaffney and Gater (2003) and Milsom and Eriksen (2011).

Electrical methods

Electrical methods can be either passive (e.g., self-potential techniques that measure equipotential surfaces) or active (direct current resistivity or induced polarization techniques). Soil resistivity techniques utilize various electrode configurations to send electrical current into the ground while measuring the variation in subsurface electrical resistivity based on Ohm's law. Electrode arrays are capable of penetrating to greater depths by increasing the electrode spacing. Electrical current is conducted within the subsurface, and resistivity meters register either high- or low-resistance anomalies, compared to the background soil resistance, due primarily to low or high water content, respectively, which is a result of either the presence of stone structures and voids or concentrations of clay and organic material within ditches and pits. Soil resistance techniques can be used in different modes: vertical electric soundings (VES), resistivity profiling or mapping, and electrical resistivity tomography (ERT). ERT has been increasingly employed in the last few years to provide a 3D resistivity reconstruction of the subsurface through the use of inversion techniques (Sarris, 2008).

Magnetometry

Magnetometry is based on the detection of weak local variations of the Earth's magnetic field caused by either the concentration of ferrous metal artifacts, the presence of building materials containing higher or lower concentrations of magnetic oxides, the thermomagnetic remanence of the past magnetic signature of the Earth's field, or the enhancement of the magnetic susceptibility of soils (Thompson and Oldfield, 1986). Measurements can be carried out with a variety of instruments, measuring either the total magnetic field–proton free precession magnetometers, optically pumped alkali/cesium vapor magnetometers, and SQUIDs (superconducting quantum interference devices) or one of its components, usually the vertical (fluxgate gradiometers). SQUID and alkali vapor magnetometers offer a much higher sensitivity.

Magnetic susceptibility

Complementary to magnetic surveys, magnetic susceptibility is employed to detect single-domain grains of soil that are related to past human activity in order to draw conclusions on the intensity or the multiple phases of occupation in a settlement. In addition, it can define areas of industrial land use and predict the potential success of a magnetometer survey within an archaeological site. Magnetic susceptibility measurements are often carried out in parallel with chemical analysis of soils because a number of chemical constituents such as phosphate, zinc, pH, calcium, magnesium, iron, copper, and potassium can be used as markers for anthropogenic activities, such as workshop activities, farming, and animal husbandry. Phosphate analysis is the most commonly used, as it is considered a proxy for animal husbandry activities. Applied either in a macro- or microscale survey, and sometimes in tandem with surface surveying (concentration of bones, scatters of ceramics, etc.), field geochemical surveys can provide suggestions about the extent of sites, land use practices, and the function and intensity of occupation.

Electromagnetic systems

Electromagnetic (EM) systems, the most popular being conductivity meters, are capable of simultaneously measuring both soil conductivity and magnetic susceptibility by generating time-varying magnetic fields (usually < 30 kHz). Penetration depth depends on the separation distance between transmitter and receiver coils and their orientation, but newer systems that can operate at different frequencies are capable of penetrating to various depths. Pits, metal artifacts, and areas of high moisture content are easily detectable through EM methods. Electromagnetic sensors include pulse induction meters (such as metal detectors) that use short step changes in the electrical field and very-low-frequency (VLF) transmitters that employ a receiver separate from the transmitter source.

Ground-penetrating radar

Ground-penetrating radar (GPR) is a specific EM technique that emits high electromagnetic frequencies ($\sim$50–1000 MHz) to map the stratigraphy of the subsurface, locate discrete objects, or even detect fracture zones in monuments. The velocity of propagation for radar waves is a function of the soil's conductivity, dielectric permittivity, and magnetic permeability. GPR waves reflected from the various strata or objects beneath the ground provide information regarding the vertical extent of the targets. Parallel radargrams formed through the registration of the amplitude of the reflected signals can be combined to yield information on the horizontal extent of remains at various depths (depth or time slices). Architectural vestiges, cavities, tombs, and voids can be easily detected through GPR techniques. Antennas using lower frequencies (longer wavelengths) are also used for mapping the ancient geomorphology (e.g., ancients ports filled with alluvial deposits), usually in correlation to ERT or seismic techniques (Shahrukh et al., 2012).

Seismic methods

Seismic techniques exploit the travel times of reflected or refracted acoustical waves via a series of geophones located on the ground surface, making them appropriate for studying the stratigraphy of the ground and revealing large underground structures. Seismic techniques estimate the variation in the velocity of propagation of acoustical waves passing through the ground, and thus they provide estimates of the location and the depth of subsurface targets.

Microgravimeters

Microgravimeters are employed for revealing weak variations in the Earth's gravitational field (1–200 μgals out of a total of about 9.8×10^8 μgals) which may be related to the presence of voids, cavities, tunnels, or other buried solid architecture that are responsible for changes in mass density with respect to the surrounding soil matrix. Microgravity techniques have also been applied in the detection of buried chambers within large monumental structures. Since localized variations in topography and the presence of other structures influence the values of gravity, high-resolution mapping of the terrain and nearby buildings is necessary in order to apply corrections to the corresponding measurements (Pánisová et al., 2013).

Discussion

Seismic, GPR, ERT, and magnetic susceptibility measurements have been taken within boreholes in order to provide information regarding the stratigraphy of archaeological sites and to delineate their characteristics at particular depths. Other measurements have been reported in the literature, varying from radiometric methods to thermal imaging. Whatever the case, the archaeological interpretation of geophysical results is often enhanced when more than one technique is applied, since the use of varied measurements can provide complementary information by focusing on different properties. Recent trends with geophysical methods have focused on the speed of the survey and the use of towed multi-sensor, multi-antenna, multi-electrode systems. Undoubtedly, coupled with real-time kinematic differential global positioning system (RTK DGPS) measurements, these systems offer fast and high-resolution coverage of sites. Other systems focus on using multifrequency signals capable of penetrating the subsurface to multiple depths.

Geophysical techniques can be coupled with other means of remote sensing, such as aerial and satellite imagery. Both have proven effective for recognizing site locations based on subtle differences in topsoil characteristics, which are mainly caused by variations of soil texture or vegetation stress that create soil and crop marks. Imaging the surface through the visible or non-visible (e.g., infrared or radar) portions of the electromagnetic spectrum provides spectral signatures that can be correlated with the presence of archaeological features. Together with LiDAR (light detection and ranging) sensors, which contribute to the construction of digital elevation models (DEM), airborne and satellite remote sensing contribute to the mapping of sites, the study of regional settlements, cultural resource management practices, etc. The synthesis of these multiple datasets is facilitated through the use of geographical information systems (GIS), the spatial tools of which provide useful information for the geomorphometric attributes of the terrain and other elements that have a direct consequence for site-catchment analysis and settlement pattern modeling and in constructing predictive habitation models (Sarris, 2008).

Summary

Geophysical techniques used for archaeological prospection make use of the measurements of almost all physical quantities where the existence of archaeological sites or past human activity has modified the background values. Efforts have been made to amalgamate, combine, and invert diverse datasets that originate from the use of different methodologies. This kind of integrated approach is capable of increasing the confidence level of data interpretation.

The current trend in archaeological geophysics has been moving toward rapid reconnaissance of sites in order to reduce the time involved while obtaining accurate information, but there remain many challenges to address. Multi-method systems may offer higher resolution and faster coverage of sites, but they are deficient in ways that need particular attention (e.g., urban surveys, rocky environments, rough terrain, medium depth to deep mapping). Yet, the use of manifold geophysical strategies will continue to provide complementary evidence of the subsurface in order to address a wide range of archaeological questions (Sarris, 2012).

Archaeological prospection inherently encounters problems from later human disturbances of sites as well as various geological processes that make it difficult to resolve a useful signal from background noise, especially when the site incorporates complex, multiple habitation phases. This may impose a limit on the use of geophysical techniques, but they currently play, and undoubtedly will continue to play, a primary role in archaeological landscape studies.

Bibliography

Clark, A. J. C., 1990. *Seeing Beneath the Soil: Prospecting Methods in Archaeology*. London: Batsford.

Gaffney, C. F., and Gater, J., 2003. *Revealing the Buried Past: Geophysics for Archaeologists*. Stroud: Tempus.

Linford, N., 2006. The application of geophysical methods to archaeological prospection. *Reports on Progress in Physics*, **69**(7), 2205–2257.

Milsom, J. J., and Eriksen, A., 2011. *Field Geophysics*, 4th edn. Hoboken: Wiley.
Pánisová, J., Fraštia, M., Wunderlich, T., and Pašteka, R., 2013. Digital photogrammetry in microgravity data processing: a case study from St. Catherine's Monastery, Slovakia. In Neubauer, W., Trinks, I., Salisbury, R. B., and Einwögerer, C. (eds.), *Archaeological Prospection: Proceedings of the 10th International Conference, Vienna, May 29–June 2, 2013*. Wien: Austrian Academy of Sciences, pp. 330–333.
Sarris, A., 2008. Remote sensing approaches/geophysical. In Pearsall, D. M. (ed.), *Encyclopedia of Archaeology*. New York: Academic Press, Vol. 3, pp. 1912–1921.
Sarris, A., 2012. Multi+ or manifold geophysical prospection? In Computer Applications and Quantitative Methods in Archaeology (CAA) Conference, March 26–29, 2012, University of Southampton.
Scollar, I., Tabbagh, A., Hesse, A., and Herzog, I., 1990. *Archaeological Prospecting and Remote Sensing*. Cambridge: Cambridge University Press.
Shahrukh, M., Soupios, P., Papadopoulos, N., and Sarris, A., 2012. Geophysical investigations at the Istron archaeological site, eastern Crete, Greece using seismic refraction and electrical resistivity tomography. *Journal of Geophysics and Engineering*, **9**(6), 749–760.
Thompson, R., and Oldfield, F., 1986. *Environmental Magnetism*. London: Allen and Unwin.

Cross-references

Anthrosols
Electrical Resistivity and Electromagnetism
Field Geochemistry
Geographical Information Systems (GIS)
Ground-penetrating Radar
Magnetometry for Archaeology
Paleoenvironmental Reconstruction
Remote Sensing in Archaeology
Susceptibility

GESHER BENOT YA'AQOV

Nira Alperson-Afil
The Martin (Szusz) Department of Land of Israel Studies and Archaeology, Bar Ilan University, Ramat-Gan, Israel

Gesher Benot Ya'aqov

Gesher Benot Ya'aqov (GBY) is an Early-Middle Pleistocene archaeological site located in the course and on the banks of the Jordan River, Israel. Seven excavation seasons (1989–1997) under the direction of Naama Goren-Inbar exposed a 34 m depositional sequence in which 15 archaeological levels were recorded. Tectonic activity on the transform fault of the Dead Sea Rift resulted in the tilting of the GBY strata. The oblique archaeological horizons are embedded within a generally fine-grained sedimentary sequence that documents rapid shifts in abundance of carbonate and organics typical of a low-energy fluctuating lake margin environment (Feibel, 2004).

The GBY sequence consists of a reversed-polarity zone overlain by a normal-polarity zone correlated with the 0.79 Ma Matuyama-Brunhes chron boundary; the entire depositional sequence is assigned to OIS (oxygen isotope stages) 18–20, and its estimated duration is ca. 100,000 years. Archaeological data indicate that hominins regularly occupied the lake margin (paleo-Lake Hula) during Lower Paleolithic times.

The lithic assemblages of GBY are attributed to the Acheulian cultural complex, during which the earliest human migrations into the Levant occurred through the Levantine Corridor as a migration route out of Africa and into Eurasia (Goren-Inbar et al., 2000). The lithics of GBY thus exhibit typological and technological similarities to their African counterparts. These include a variety of cores and core tools, bifacial tools (handaxes and cleavers), and flakes and flake tools modified on different raw materials (flint, basalt, and limestone).

The paleontological assemblages include mammals (e.g., elephants, rhinos, cervids, bovids, hippos, equids, and micromammals) as well as birds, fish, crabs, and mollusks. A skull of a straight-tusk elephant (*Palaeoloxodon antiquus*) was found with its rear part (the brain case) absent (Goren-Inbar et al., 1994). Large quantities of cranial bone splinters were obtained from sediments next to the skull, suggesting battering and processing of the skull. Assemblages of fallow deer (*Dama* sp.) illustrate systematic and repeated utilization of complete carcasses by the GBY hominins. Cut marks, percussion marks, and hack marks on the bones and their anatomical position suggest that carcass processing followed systematic practices that reflect in-depth knowledge of fallow deer anatomy (Rabinovich et al., 2012).

The unique waterlogged environment of GBY preserved rich botanical assemblages including wood and bark (27 species of trees, shrubs, and woody climbers) and over 130 species of fruits, nuts, and seeds (Goren-Inbar et al., 2002a). A man-made polished wooden plank of a willow tree (*Salix*) (25 × 13.5 × 4 cm) was also recovered (Goren-Inbar et al., 2002b).

Early use of fire is recorded throughout the long stratigraphic sequence (Alperson-Afil, 2008; Alperson-Afil and Goren-Inbar, 2010). Burned flint microartifacts occur in dense concentrations interpreted as the remnants of ancient phantom hearths. The repetitive use of fire indicates that the hominins of GBY had a profound knowledge of firemaking. Spatial analyses of the variety of archaeological finds indicate that the GBY hominins differentiated their activities across space (Alperson-Afil et al., 2009). These activities were organized in discrete locations including those associated with hearths.

Bibliography

Alperson-Afil, N., 2008. Continual fire-making by hominins at Gesher Benot Ya'aqov, Israel. *Quaternary Science Reviews*, **27** (17–18), 1733–1739.

Alperson-Afil, N., and Goren-Inbar, N., 2010. *The Acheulian Site of Gesher Benot Ya'aqov*. Dordrecht: Springer. Ancient Flames and Controlled Use of Fire, Vol. II.

Alperson-Afil, N., Sharon, G., Kislev, M., Melamed, Y., Zohar, I., Ashkenazi, S., Rabinovich, R., Biton, R., Werker, E., Hartman, G., Feibel, C., and Goren-Inbar, N., 2009. Spatial organization of hominin activities at Gesher Benot Ya'aqov, Israel. *Science*, **326**(5960), 1677–1680.

Feibel, C. S., 2004. Quaternary lake margins of the Levant Rift Valley. In Goren-Inbar, N., and Speth, J. D. (eds.), *Human Paleoecology in the Levantine Corridor*. Oxford: Oxbow, pp. 21–36.

Goren-Inbar, N., Lister, A., Werker, E., and Chech, M., 1994. A butchered elephant skull and associated artifacts from the Acheulian site of Gesher Benot Ya'aqov, Israel. *Paléorient*, **20**(1), 99–112.

Goren-Inbar, N., Feibel, C. S., Verosub, K. L., Melamed, Y., Kislev, M. E., Tchernov, E., and Saragusti, I., 2000. Pleistocene milestones on the out-of-Africa corridor at Gesher Benot Ya'aqov, Israel. *Science*, **289**(5481), 944–947.

Goren-Inbar, N., Sharon, G., Melamed, Y., and Kislev, M., 2002a. Nuts, nut cracking, and pitted stones at Gesher Benot Ya'aqov, Israel. *Proceedings of the National Academy of Sciences*, **99**(4), 2455–2460.

Goren-Inbar, N., Werker, E., and Feibel, C. S., 2002b. *The Acheulian Site of Gesher Benot Ya'aqov*. Oxford: Oxbow. The Wood Assemblage, Vol. I.

Rabinovich, R., Gaudzinski-Windheuser, S., Kindler, L., and Goren-Inbar, N., 2012. *The Acheulian Site of Gesher Benot Ya'aqov*. Dordrecht: Springer. Mammal Taphonomy, The Assemblages of Layers V-5 and V-6, Vol. III.

GLACIAL SETTINGS

Christopher L. Hill
Graduate College, Boise State University, Boise, ID, USA

Introduction

The growth and melting of continental and mountain glaciers, as well as the related environmental changes that occur as part of these episodic fluctuations, influence the habitability of certain landscapes by humans and play a role in the formation of archaeological sites. The processes connected with glaciers have an impact on the types of settings used by humans and on the preservation and visibility of archaeological sites. At times, large regions of the northern hemisphere were covered by continental glaciers during the Quaternary, i.e., the last several million years. In addition, mountain glaciers and ice fields are found on every continent. They have played a critical role in (1) the development of glacial theory and (2) climate change and the study of human-environmental relationships.

Glaciers are moving accumulations of ice originating from snowfall. They are moving masses of ice, in contrast to nonmoving ice fields and ice patches. As glaciers move across a landscape, they erode and scour the earth, transporting and then depositing sediments. Sediments can be deposited by the direct action of glaciers, or they can be deposited indirectly as, for instance, outwash sediments carried in meltwaters. When a glacier expands over a landscape that contains archaeological sites, these sites can be preserved, transformed or altered to various degrees, or destroyed by the actions of the glacier.

There are three major forms of glaciers: mountain glaciers, valley glaciers, and continental ice sheets. Today, mountain glaciers are found on all continents and are connected with various human activities. During global cold events, glaciers expanded from the mountains into the valleys and mountain fronts. Some glaciers merged to form larger, continental glaciers, including the Cordilleran and Laurentide Ice Sheets in North America and the Scandinavian Ice Sheet in Eurasia.

Glacial settings consist of both glaciated terrains and areas subjected to proglacial and periglacial conditions. Proglacial areas are adjacent to glaciers, while periglacial conditions occur in areas of frozen ground regardless of proximity to a glacier. Each of these settings contains particular sedimentological and geomorphic contexts that can be related to human use of the landscape. Glaciers and the physical record of glaciation are *key types of evidence* for local environmental change, and global warming and cooling. Glacial settings are important for geoarchaeological studies because (1) they provide a temporal framework associated with environmental change and humans, (2) they can be used to document landscapes (habitats and resources) that were present in the past, and (3) they are useful in studies of the dynamics of landscape evolution and human land use. After a summary of research history, this review focuses on erosional and depositional processes connected with glaciation and the glacial settings associated with human activities.

History of glacial theory and its importance to geoarchaeology

The discovery that vast expanses of the earth had been covered by glaciers in ancient times played an important role in the history of geoarchaeology. Louis Agassiz is usually credited with promoting the Ice Age Theory. His proposal of a "Great Ice Age" as a time of expanded glaciers at the 1837 meeting of the Swiss Society of Natural History was based on his own field observations and the studies of Jean de Charpentier in the alpine regions of Europe. Prior to this, James Hutton (in 1795) and John Playfair (in 1802) had interpreted erratic boulders found in the Alps as evidence of expansion of mountain glaciers. Based on observations in the mountains of Norway, Jens Esmarkin (in 1824) proposed that there had been much larger glaciers in the region in the past. Ignatz Venetz (in 1829) proposed that both the Alps and northern Europe had once been glaciated, and A. Bernhardi (in 1832) argued that erratic boulders found in Germany were deposited by glaciers. Similar conclusions were made by J. de Charpentier (in 1834) and

Karl Schimper (in 1837). Schimper has been credited for first using the term *Eiszeit* or "ice age."

In 1840, Agassiz published *Études sur les Glaciers* and conducted fieldwork in Britain with Roderick Murchison and William Buckland, providing evidence of glaciation in this region. In 1846, Agassiz recognized the evidence of glaciation in North America, the same year that Edward Forbes used the term "Pleistocene" as the equivalent of the Glacial Epoch, the time of ice-age deposits. In 1847, Agassiz argued that the glaciers from northern Europe and the Alpine region of Europe were the result of independent glacial sources.

The initial concept of an ice age was as a single climate event, but in the late 1840s and early 1850s, studies in eastern France, Switzerland, Wales, and Scotland documented the existence of two glaciations separated by an interglacial period. This evidence, in areas of glaciated terrain, included a stratigraphic sequence containing two tills, or deposits of glacial sediments, separated by interglacial deposits. The first extensive overview of glacial stratigraphies was James Geikie's *The Great Ice Age* in 1874 that evaluated deposits and landforms under present conditions in Greenland, causes of the Ice Age, and stratigraphic sequences throughout Europe and North America, with a focus on Scotland. This text was revised several times, but by 1877, Geikie was arguing the stratigraphic evidence indicated at least four and perhaps five major intervals of glaciation with intervening interglacials. (A similar text, *The Ice Age in North America*, was published by G. F. Wright in 1889.)

By 1882, Albert Penk had identified three glaciations in the Alps and had mapped the general limits of glaciation in Europe and some other parts of the world. Using a sequence of terraces connected with the rivers Günz, Mindel, Riss, and Würm, Penck and Eduard Brückner developed the classic glacial series in the first decade of the 1900s. Moraines, glaciofluvial deposits, and terraces in the foothills of the Alps were used by Penck and Brückner to document a sequence of glacial episodes (labeled Günz, Mindel, Riss, and Würm) alternating with interglacials. During the first half of the nineteenth century, this framework was applied to other regions and served as the basis for global correlations, until marine stable isotope records demonstrated that the interpretation of a fourfold terrestrial sequence was an oversimplification of the global record of Quaternary glacial-interglacial cycles. The equivalent fourfold sequence of continental glaciation in North America (Nebraskan, Kansan, Illinoian, and Wisconsinan) was partly abandoned in the 1970s and 1980s, and the terms Nebraskan and Kansan are not commonly applied today. Illinoian continental ice sheet glacial advances are often correlated with Bull Lake advances in the mountains of western North America, while Wisconsinan advances are correlated with the Pinedale mountain glaciations. This glacial and non-glacial framework developed since the 1880s is critical to a geoarchaeological view focused on relations between humans and past environments.

Essential concepts: glacial processes (sediments and landforms)

Glaciers originate as the result of the deep accumulation of snowfall densely packed by gravity. Glaciated terrains exhibit various erosional and depositional features that provide evidence of past landscape processes. These same landscape processes may have an influence on the formation and preservation of the archaeological record (Ashley et al., 1985; Hambrey, 1994; Ehlers, 1996; Bennett and Glasser, 2009). Abrasion by glaciers creates striations (scratches), polish, crescentic marks or chattermarks on bedrock surfaces, and larger erosional features such as whalebacks, stoss-and-lee forms (*roches moutonées*), crag-and-tail, drumlins, and ice-thrust features. Erosion also occurs on a broader scale, contributing to the character of the landscape and forming U-shaped or parabolic valley cross sections and fjords. Eroded materials may include unconsolidated sands, silts, clays mixed with larger gravels, cobbles, and boulders, all deposited and reworked as glaciers advance and recede. Meltwaters move and redeposit these materials, as wind and ice lift new materials from the ground surface. Thus, glacial erosion processes provide evidence of the extent and dynamics of previous glaciations and can lead to the incorporation, transport, and redisposition of archaeological materials.

Rock fragments that are different in composition compared to the underlying bedrock are defined as *erratics*. These can provide an indication of the dispersal direction and origin point of the glacier. For instance, distinctive fragments of Oslo district and Dala porphyry bedrock found in Germany show the southward dispersal path of the Scandinavian glacier, while Precambrian rocks found in northern Montana are derived from glaciers moving southward from Saskatchewan, Canada. Besides being used to trace the route of glacier movement, erratics can be used by people as raw materials for tools and structures (Williams-Thorpe et al., 1999). For instance, the blocks used in the construction of Stonehenge may have been transported by glaciers from their original bedrock source (Kellaway, 1971).

Materials eroded by glaciers result in sedimentary deposits and distinctive landforms which provide clues about past landscapes. The term *drift* was applied historically to designate materials deposited directly by glacial ice as well as sediment resulting from glacial meltwater. *Till* is nonstratified sediment directly deposited by glacial action; such sediments are transported and deposited by glacier ice with no sorting by water. Historically, it was also referred to as boulder clay, and it is often texturally heterogeneous and unsorted, containing a wide range of particle sizes (the term *diamicton* is used to describe poorly sorted sediments regardless of origin).

Stratified deposits, in contrast, exhibit size sorting of constituent particles and are usually associated with direct transport and deposition by water. These include ice-contact as well as proglacial sediments. Thus, *stratified* *drift* (for instance, glaciofluvial outwash deposits) may extend beyond the area of glaciated terrain forming *sandar* (Icelandic term used to indicate proglacial outwash plains) and braided stream channels. Sediments deposited in lakes dammed by ice or formed along the margin of a glacier are also stratified drift. These deposits can be well sorted but vary in particle size, which can reflect whether they are deltaic, littoral, or deeper water deposits.

Depositional landforms produced by glacial activity include *moraines*, *kames*, *kame terraces*, *kettles*, and *eskers*. A ground moraine is deposited on land surfaces covered by the glacier and is an accumulation of sedimentary particles of various sizes. End moraines, either lateral or terminal, mark the margin of a glacier. A recessional moraine is formed during a halt in the melting of a glacier. Kames and kame terraces consist of stratified sediments and are ice-disintegration features found at the margin of a glacier; kames represent sediment deposited within depressions atop a retreating glacier that eventually become mounds on the ground surface with further glacial melting, while kame terraces are linear glaciofluvial ice-contact ridges that form along the sides of glaciers between the ice and valley slopes. Kettles are closed depressions formed by the melting of a block of glacier ice that separated from the glacier and became buried within outwash sediments; the holes created by the melting block indicate a landscape that was subjected to ice decay. Eskers are linear landforms composed of sediments deposited by streams in tunnels below glaciers or confined on their sides by ice; these are usually elongate ridges filled with sediments and are ancient subglacial meltwater streams.

Deposits and landforms associated with glacial lakes are widespread in areas that were previously at the margins of continental glaciers. In Europe, the southern margin of the Weichselian phase of the Scandinavian Ice Sheet was bounded by the Baltic Ice Lake. In North America, an extensive series of glacial lakes developed along the Wisconsinan margin of the Laurentide ice sheet. The largest of these was proglacial Lake Agassiz. Landforms associated with glacial lakes include flat plains formed by lake-bottom sediments, shorelines, and deltas. The "parallel roads" of Glen Roy in Scotland are well-known examples of abandoned shorelines created by changing water levels in an ice-dammed lake.

Glacial isostatic downwarping or deformation of the Earth's crust was caused by the weight of the Scandinavian and Laurentide ice sheets. Since melting of the continental ice sheets, the land has rebounded. In uplifted regions that contain glacial lakes, shorelines are tilted or inclined because of isostatic rebound. Isostatic adjustment also causes changes in the base levels of streams. Detailed uplift studies have been undertaken in Scandinavia and Britain (Steffen and Wu, 2011). In North America, the tilted shorelines of Lake Agassiz, glacial lakes in the Great Lakes region, and the New England coastal area have been studied for their geoarchaeological potential (Phillips and Hill, 2004; Lovis et al., 2012). In glaciated coastal areas, deglaciation and flooding caused by rising sea levels combined with isostatic rebound results in the exposure of marine sediments. This leads to different landscape histories in areas within and beyond the limits of deposition of marine sediments. These differences in landscape evolution have an effect on the visibility and preservation of archaeological sites.

Landforms and sediments that are the result of cold climate conditions beyond the limit of glaciation are important settings in geoarchaeology since they are areas that were often close to active glacial processes and also inhabited by humans. In glaciated terrain and areas that were previously adjacent to glaciers or permafrost regions (areas with frozen ground), distinct geologic features are formed. These features include either frost-wedged debris or other shatter, such as taluses, rock glaciers, and angular rubble in caves. *Downslope mass movement* refers to the transport of earth downhill, often resulting in zones of erosion and zones of accumulation. Downslope movement of water-soaked ground by *solifluction* (soil flow) results in destruction of primary sedimentary features and original stratigraphy. This happens because meltwater blocked by frozen ground saturates the soils, which flow down hills in solifluction lobes. *Cryoturbation* is the mixing of sediments and soils by the action of ice and is reflected by involutions and contorted stratigraphy. Some distinctive structures that form as the result of frost action are frost cracks or ice wedge casts, *pingos*, and patterned ground. Ice wedges are used as an indication of former permafrost and lower temperatures. Pingos are the result of ice-cored mounds; in periglacial areas, permafrost rises toward the ground surface forcing pore water upward, which in turn pushes the ground upward gradually as the ice core slowly grows in height. Patterned ground features also are formed in cold regions and are usually associated with frost heaving and cracking resulting in patterns of angular, fragmented rocks (Bertran et al., 2010). Rock debris sorted into piles of stone by frost action (patterned ground) can be reminiscent of archaeological features. For instance, areas with large rock fragments and some vegetation can form semicircular stone pits or stone-banked terraces, while areas with little vegetation can form sorted stone rings or circles and stone streams.

Extent of glaciation and glacial temporal framework

Presently, glaciers cover around 10 % of the Earth's land surface and contain almost 75 % of the fresh water supply. There are about 92 million km^2 of land on Earth, and it is estimated that about 26 million km^2 were glaciated about 20,000 years ago; thus, ice covered as much as 28 % of total land area during the most recent major glacial episode. Today, most of the ice is in the Antarctic and Greenland, with the rest in alpine regions and polar sea ice caps.

During the last major glaciation, virtually all of Canada, as well as some of the northern areas of the United States, were covered by ice sheets. The Laurentide ice sheet at times covered almost all of Canada east of the Rocky Mountains with lobes of ice advancing southward to the northern Great Plains, Great Lakes, and New England regions (Hill, 2006a, b, c). The Cordilleran ice sheet formed in western Canada and the adjacent regions of the northern United States.

Besides North America, glaciers have formed on every other continent. In South America and Africa, glaciers expanded from the mountain regions (Ehlers and Gibbard, 2004a; Ehlers and Gibbard, 2004c; Ehlers and Gibbard, 2011). For example, the Patagonian Ice Sheet covered Chile and much of Argentina. In northern Europe, the Scandinavian Ice Sheet extended southward into Germany, Poland, and Russia. Independent glaciers formed in the highland and mountain regions of Europe, the largest in the Alps. Britain had several ice centers, and Iceland was covered by glacial ice. There is little physical evidence for continental-scale ice sheets in northern Asia, although glaciers formed in highland and mountain regions. The absence of continental ice sheets may be partially related to lower amounts of available moisture. Nevertheless, many mountain areas in Asia experienced intensified glacial activity during the Quaternary, including glaciers in Turkey, the Caucasus Mountains, the Sayan (Altai) Mountains, the Vitim Plateau, the Yablonovy Mountains, the Stanovoy Mountains, the Aldan/Dzhug-Dzhur Mountain complex, the Putorana Mountains, the Verkhoyansk-Chersky region, and the Kamchatka Mountains.

The glacial and postglacial time framework has been refined by comparing evidence of glaciation on land with the more complete and continuous ocean record of global climate change and by using several dating techniques. Prior to the availability of radiocarbon dating, the postglacial time framework was estimated using a varve chronology. A varve consists of two layers of sediment that form in 1 year. It is a seasonal pair of layers deposited in still water, such as a proglacial lake or a kettle depression. The study of varve sequences in glaciated northern Europe and North America provided a constraining age for the timing of deglaciation; by counting a sequence of varves and correlating from basin to basin, it is possible to determine the beginning of sedimentation in a basin in a glaciated landscape. These chronologies were used as the basis for broad ranging geomorphic correlations prior to the advent of radiocarbon dating. The varve dating method was pioneered by Gerard De Geer in Sweden starting in 1905 and was refined by the work of Matti Sauramo in Finland in the 1920s. Varve chronology provided the first age estimates for the Allerød and Younger Dryas events, well before the use of radiocarbon dating. Ernst Antevs started using varves in the 1920s in North America as a way to estimate the amount of time since deglaciation.

The global-scale climate record, based on the stable isotope curve from the ocean floor, is used for linking glacial sequences on land; however, local and regional terms are still applied. For any particular glaciated area, there are special terms assigned to sedimentary deposits or lithostratigraphic units, landforms, glacial lobes (tongues of ice), ice margins, and phases of ice advance, as well as an array of designations for lakes, lake phases, *stadials* (a cooler interval within a time of warm climate), and *interstadials* (a warmer interval within a glacial episode).

Typically, local names have been used to designate the various episodes of mountain and continental ice sheets throughout the world. For instance, the last major expansion of the Scandinavian Ice Sheet is called the "Weichselian," a German reference to the Vistula River in Poland, where glacial deposits now estimated to date to about 20,000 years ago were first described in the early 1900s. In the North American Rocky Mountains, the youngest major Pleistocene glaciation dating to about this time is termed "Pinedale," based on a local name, while in the Pacific Northwest, the "Fraser" glaciation is usually associated with the most recent Pleistocene glaciation. Even within major intervals of glaciation, there were advances and retreats of ice lobes or ice sheet margins. An important example is the Younger Dryas which is used to designate a short, cold period at the very end of the Pleistocene. The age of the Younger Dryas has been measured using varves and radiocarbon dating. The Younger Dryas dates to about 11,000–10,000 ^{14}C BP, right before the start of the Preboreal, which was the beginning of the Holocene. The term *postglacial* refers to the time after a glacier had melted from a local area and is a relative time designation since some areas were deglaciated before others. It signifies the time after a glacier had retreated, leaving a landscape available for colonization by plants and animals, including humans.

Applications: glacial settings and geoarchaeology

Glacial settings consist of landforms and sediments produced above or below glaciers (supra- and subglacial), those formed in contact with ice margins, and those under proglacial and periglacial conditions. These can include areas of little or no erosion, as well as areas of intense erosion or deep deposition. Kames and hummocky terrains may reflect rock debris that once rested on top of glaciers. Drumlins and eskers are associated with subglacial settings. Indications of ice-marginal areas are terminal moraines and outwash fans. Glaciofluvial settings are associated with eskers, meltwater channels, kames, kame terraces, and outwash fans. Proglacial lakes are associated with shorelines, deltas, outwash fans, laminated sediments, varves, rain out from ice rafting, and meltwater channels. Ice-stagnation features associated with ice disintegration and deglaciation of a landscape have the potential to be linked to landscape habitability.

Glaciated terrain and postglacial landscapes

There have been instances when glacial ice expanded over a region that was previously inhabited by people, and, consequently, archaeological deposits were removed from their original context. Under these circumstances, artifacts were incorporated into younger glacial tills and outwash or redeposited in other younger sediments. The Paleolithic site of High Lodge located in eastern England contains blocks of sediment bearing Mousterian artifacts that were glacially transported intact and laid down over younger deposits (Ashton et al., 1992; Roe, 1993). Eroded and transported Acheulian artifacts were then incorporated into glaciofluvial and debris flow deposits that actually buried the Middle Paleolithic sediments, creating a confusing situation where presumed older Acheulian artifacts were recovered above younger Mousterian artifacts. While the Middle Paleolithic artifacts had been moved, they were still incorporated in their original block of sediment, in contrast to the Acheulian materials, which were in a secondary position, as a result of glaciofluvial processes.

Other sites are associated with reworked glacial sediments. For instance, the Norse settlement of L'Anse aux Meadows is in a region of Newfoundland with glacially modified bedrock and recognizable glacial deposits, but the site itself is situated on beach and terrace deposits composed of reworked till (Davis et al., 1988; Kristensen and Curtis, 2012). The Dundee Canal site in New Jersey is underlain by outwash deposited by melting ice of the Augusta-Mud Pond recessional moraine; reworked till and outwash were the sources for the overlying sediments containing artifacts (Thieme, 2003). There are also instances of glacial advances leading to the burial of ancient landscapes. In England, the stumps of trees and fossils dated to the Middle Pleistocene Cromerian interglacial are overlain by glacial till. The buried Cromerian Forest dates to before 478,000 years ago and is sometimes correlated with the warmer environments between the Günz and Mindel glaciations in the European Alpine region, possibly correlated with global isotope stages 21–13. Lower Paleolithic Acheulian artifacts are found in Cromerian deposits (Moir, 1924; Stout et al., 2014).

The glacial setting associated with the Cordilleran ice sheet in western North America is an important area for testing the idea that late Pleistocene human groups could have traveled along the Pacific coast from Beringia to unglaciated regions farther south (Fedje et al., 2011). The question to be tested is whether there is evidence of environments that would have been suitable for human presence along the glaciated coast. The dynamics of glaciation along the Pacific coast have been examined in terms of potential landscapes for late Pleistocene human migration, although interpretations are complicated by the effects of eustatic sea-level changes, isostatic depression and uplift, and local tectonics (Hill, 2006a; Fedje et al., 2011). During the late Wisconsinan, glaciers advanced westward from the mountains onto the coastal areas. In some regions of Alaska and British Columbia, the forebulge effect along the margins of expanding glaciers resulted in the presence of inhabitable landscapes. A forebulge is a rising land level at the margins of an area under glacial load. At On Your Knees Cave, on Prince of Wales Island, radiocarbon-dated bones of brown bears indicate that they were able to inhabit the area throughout the Frasier Glaciation, the local equivalent of the last major Pleistocene glaciation. Even though the area was surrounded by the Cordilleran ice sheet, there seems to have been an unglaciated coastal habitat that could sustain large mammals. Port Eliza Cave on Vancouver Island contains a stratigraphic sequence with till indicating the onset of glaciation around 16,000 ^{14}C BP and deglaciation by 12,500 ^{14}C BP, implying this coastal region would have been unavailable only for about 3,000 years (Al-Suwaidi et al., 2006). The islands between the Washington mainland and Vancouver Island also contain fossils of large mammals, indicating the habitability of this deglaciated landscape. At Ayer Pond, glaciomarine drift is overlain by lake deposits containing bones of an extinct form of bison dating to 11,990 ^{14}C BP (Wilson et al., 2009; Kenady et al., 2011). The Manis mastodon site on the Olympic Peninsula of Washington State documents the presence of humans in this deglaciated landscape by 11,960 ^{14}C BP (Waters et al., 2011). The locality contains mastodon, bison, and caribou fossils overlying late Wisconsinan Cordilleran till.

The evidence of interaction between the Laurentide and Cordilleran ice sheets in North America is particularly interesting because of the implications for deglaciated landscapes that could have been inhabitable and used as a route of movement by late Pleistocene human populations (Hill, 2006a). It is possible that an ice-free corridor was entirely open by 13,500 ^{14}C BP or possibly as late as 12,500 ^{14}C BP, suggesting it was available for human habitation even prior to the Clovis interval, which began about 11,000 ^{14}C BP (Dyke, 2004, 411; Dixon, 2013). Within the corridor region of the northern Great Plains, there are early sites that are associated with glaciated terrain. Deglaciated landscapes in Alberta, Saskatchewan, and Montana, for instance, supported a diverse biotic community by Clovis times (Hill, 2006a, d; Kooyman et al., 2006; Waters et al., 2015). Just south of the St. Mary River, artifacts and Pleistocene fauna dated to 11,450–11,320 ^{14}C BP have been recovered in windblown sands and silts capped with a *paleosol* (an ancient buried soil). In Montana, the Sun River mammoth was found in organic-rich bog deposits dating to 11,500 ^{14}C BP that formed after the melting of glacial ice that had advanced eastward out of the Rocky Mountains. The sediments containing the mammoth were deposited after the melting of the Sun River lobe of the Pinedale phase glacier, and they are overlain by a 6-m-thick sequence of alluvium interbedded with volcanic ash and colluvium. A date of 11,170 ^{14}C BP on bone recovered in deposits above the Laurentide till in the Marias River Valley suggests that this deglaciated region north of the Missouri River was a viable habitat for human land use by the time of Clovis (Hill, 2006d).

Proglacial lakes formed along the southern margin of the Laurentide Ice Sheet as it advanced southward. Along its southwest margin in Montana, different ice lobes expanded from Canada into northern Montana and North

Dakota, some extending as far south during the Last Glacial Maximum as the present location of the Missouri River. As the ice receded, lakes formed along the melting front of the glacial lobes. North of the Saskatchewan River, the Kyle mammoth is associated with glacial lake deposits. The colluvial and alluvial sediments of the Vermillion Lakes site in Alberta also lie above glacial lake sediments. In Manitoba, Folsom-Midland artifacts have been found within the basin of glacial Lake Lind. This suggests that a fairly rapid pattern of human land use accompanied the drainage of proglacial lake surfaces.

The largest proglacial lake in North America was glacial Lake Agassiz, which formed over the region of eastern North Dakota, western Minnesota, and southern Manitoba and Ontario. The lake initially filled as ice receded from the Big Stone Moraine and went through several phases and water levels based on oscillations of the southern margin of the Laurentide Ice Sheet. The highest major strandline, the Herman Beach, contains mammoth fossils, while the Lockhart phase dates to Clovis times (Buchner and Pettipas, 1990). The Moorhead low phase dating to about 10,500 ^{14}C BP is associated with the Folsom period (Boyd, 2007). A rise in the water levels during the Emerson phase brought the waters of Lake Agassiz to the level of the Campbell beach strandline and flooded the landscape exposed during the Moorhead phase. This rise in lake level after the Moorhead (Folsom-age) phase was caused by a blocking of the eastward drainage route by the Marquette advance in the Superior Basin. Because of isostatic rebound, the Lake Agassiz shorelines are tilted to the south; the uplift continues to the present day and has changed base levels for streams flowing in this region. The Rustad site in North Dakota contains artifacts and bison bones in alluvial sediments overlying Emerson phase lake deposits that bury a Moorhead phase alluvial terrace.

The region between Lake Agassiz and the Lake Superior Basin provides an example in which the dynamics of glaciation can be linked to human use of deglaciated landscapes, and postglacial conditions impact the preservation and visibility of archaeological sites (Phillips and Hill, 2004; Hill, 2007; Hill et al., 2011). Three glacial lobes of the Laurentide Ice Sheet were active in the region west of Lake Superior. While the Rainy River lobe melted northward into Canada, another lobe of ice expanded from the west toward the Lake Superior Basin, which also periodically contained glacial ice. Although mammoth remains suggest that viable environments may have been present earlier, the oldest direct indicator of human presence in this glaciated terrain of northeastern Minnesota is a Clovis point from the Cloquet River drainage. In the Superior Basin, a series of abandoned shorelines of different ages mark the changes in ancient water levels of glacial lakes. Because of isostatic rebound, the ancient shorelines are tilted; the same shoreline is higher in the north and lower in the south. Thus, archaeological sites on ancient shores of the same age will have different altitudes depending on their geomorphic location. Preservation and visibility of archaeological sites in this type of glacial setting is influenced by the changing positions of the ice margin, the differences in isostatic uplift, and lake level fluctuations (Phillips and Hill, 2004).

Fluctuations in the position of the Laurentide Ice Sheet also buried ancient landscapes. In eastern Wisconsin, the Two Creeks forest was preserved because of an advance of the Green Bay lobe. The buried forest overlies Woodfordian age till and lake clays deposited as the Green Bay lobe advanced into the region. Following a recession of the Green Bay lobe ice, shortly after 12,000 ^{14}C BP, the forest developed on the lake sediments. Around 11,750 ^{14}C BP, the forest was buried by muds and sands deposited in the proglacial lake of the advancing glacier. The lake deposits are overlain by the Two Rivers till deposited by the Greatlakean ice advance that buried the forest, which had been in existence for over 250 years.

As ice of the Lake Michigan lobe of the Laurentide Ice Sheet retreated from eastern Wisconsin, it formed the Tinley and Lake Border recessional moraines. A set of mammoth localities (Schaefer, Heboir, Mud Lake, Fenske) attest to the presence of habitable environments soon after this landscape was deglaciated. At Schaefer and Heboir, butchered mammoth bones and artifacts have been found in lake clays or peat overlying till in a topographic low between moraines. The sites date to about 12,000 ^{14}C BP, approximately the same age as the beginning of the Two Creek forest.

Other sites in the Great Lakes region provide insights into human connections with glacial and early postglacial settings (Hill, 2006b; Holliday and Mandel, 2006). In Michigan, the Holcombe site contains Paleoindian artifacts and caribou bones on the shoreline of a glacial lake behind a recessional moraine, and the Gainey site lies on the edge of a moraine near a kettle lake. The Parkhill site in Ontario, dating from between 11,000 and 10,000 years ago, lies on an abandoned shoreline. The Arc and Hiscock sites are Gainey-Clovis sites that are associated with abandoned shorelines in western New York. The Hiscock site contains mastodon remains and is situated between the Batavia and Barve moraines, while the Arc site is situated with a soil formed in till on the strandline of an ancient lake. The Burning Tree mastodon site in Ohio dating to about 11,500 years ago is in a kettle pond.

The glaciated region stretching from the Great Lakes to the Atlantic coast and northward into Canada contains examples of inland settings associated with ice-contact features and deglaciation, and the dynamic processes associated with glaciated coastal settings. In northeastern Massachusetts, the Bull Brook site is on a kame terrace and contains caribou bones with fluted points. The Vail site in northwestern Maine is located in a knob and kettle setting, adjacent to an abandoned stream channel. The Whipple site is on deglaciated terrain in New Hampshire and is situated on an alluvial terrace or delta deposit. In Nova Scotia, the Debert site overlies an ablation till and possible outwash and windblown deposits. Radiocarbon dates indicate that the locality may have been inhabited during the

Younger Dryas, a time when Nova Scotia was experiencing active glaciation and periglacial conditions (Byers, 1954; McDonald, 1968; Gramley, 1982; Curran, 1984).

As the last glacial period progressed leading up to the Last Glacial Maximum, worldwide sea levels dropped when water became stored in the ice sheets covering the continents. Sea levels dropped by about 123 m, or possibly more, and stayed around this level until the large ice sheets in North America and Europe began to melt after about 18,000 years ago. Lowered sea levels during glacial periods exposed parts of the now flooded continental shelf (Bailey and Flemming, 2008). Along the Pacific coast, in the Queen Charlotte Island region, artifacts have been found at 152 m below sea level. In the coastal Atlantic region, mastodon teeth have been recovered at 40–55 m below the present sea level on the continental shelf off Massachusetts Bay, and they have also been found on the coastal shelf adjacent to Nova Scotia (Hill, 2006c). The formerly glaciated continental shelf along eastern North America contains moraines and deposits of glacial-marine mud. In this setting, there are submerged archaeological sites that were inhabited during times when sea levels were lower than today (Kelley et al., 2010).

As with glaciated regions along the Atlantic and Pacific coastlines, other regions were subjected to both isostatic forces and eustatic sea-level changes. Parts of the North Sea floor were exposed by lowered sea levels and available to prehistoric humans. These areas have the potential for buried Paleolithic and early Mesolithic sites (Ward and Larcombe, 2008). After the melting of the Scandinavian Ice Sheet in Norway, the ice-free coastline and its resources became available. Although there is no definitive archaeological evidence of human presence before 11,500 ^{14}C BP, paleontological evidence suggests that the deglaciated Norwegian coastline ecosystem would have contained useful resources (Bailey and Flemming, 2008).

Where deglaciation has been followed by deposition of marine sediments and then isostatic uplift, such as coastal New England or Scandinavia, areas that were once flooded became inhabitable landscapes. The emergence of previously submerged areas in Maine provides a geomorphic explanation for the visibility and preservation of archaeological sites (Putnam, 1994). The differences between upland areas beyond the marine limit compared to lowland areas containing marine sediments are reflected in the landscape and the archaeological record. Likewise, in coastal Norway, there are differences in the postglacial geomorphic history and stratigraphy based on the marine limit (Sveian and Olsen, 1984; Sveian, 1997; Solberg et al., 2008). In the Trondheim region of central Norway, the Vuku substage marks the Younger Dryas and early Preboreal (the Pleistocene-Holocene boundary). A marine transgression following the recession of glaciers has led to differences in landscape history as reflected in the stratigraphy of valley fills and the distribution of landslides. These conditions lead to predictable patterns of preservation of landforms that have the potential of containing archaeological assemblages.

Periglacial settings, remains from glaciers and ice patches

Cryoturbation features, reflecting the mixing of sediments by ice action, are pervasive in archaeological stratigraphic sequences situated in past periglacial landscapes. They provide evidence of former environmental conditions and also information regarding site formation processes. Ice in soils goes through cycles of freezing and melting, resulting in frost cracking, heaving, sorting, creep, solifluction, and other forms of mass displacement. Cryoturbation processes lead to upward and lateral movement of artifacts, thus rearranging the original spatial pattern of objects within an archaeological site. Periglacial processes can modify site stratigraphy and damage artifacts and ecofacts. The Onion Portage site in northwestern Alaska provides an example of how cryoturbation distorts archaeological stratigraphy and changes the spatial arrangement of artifacts while it also provides information on environmental change (Schweger, 1985). The site is situated in the Kobuk River Valley which is filled with late Wisconsinan outwash that forms alluvial terraces 35 m above the present river. The terraces are the result of downcutting after 16,000 ^{14}C BP. The site consists of stratified floodplain (overbank) silts and windblown sands with paleosols that overlie coarse gravel outwash. Cryoturbation features at the site include frost cracks, involutions (interpenetrations of layers caused by frost action), hummocks, and the effects of solifluction. The age range for the development of involutions and solifluction activity ranges from before 8,400 ^{14}C BP to about 5,800 ^{14}C BP (Schweger, 1985). In the periglacial environment of northeastern Canada, the late Holocene Paleoeskimo site of Tayara has been subjected to downslope mass movement caused by solifluction (Todisco and Bhiry, 2008). Postglacial marine sediments have been reworked by solifluction at three separate intervals linked to short-term climatic fluctuations. While waterlogging related to solifluction may have led to its abandonment, burial by solifluction also promoted the preservation of the archaeological components. The stratigraphic record at Kents Cavern in southwestern England contains Acheulian artifacts as well as evidence of periglacial activity in the form of frost heave, solifluction, and frost-shattering (Lundberg and McFarlane, 2007).

Cryoturbation has also had an impact on archaeological sites, for example, in the Rocky Mountains, France, and in Russia. The stratigraphic sequence at the Fourth of July Valley site, in the Colorado Front Range, was almost continually affected by frost-sorting, which at times increased in intensity. Artifacts were moved upward in the stratigraphy by upfreezing (cumulative forcing of buried objects to higher levels due to the pressure of freezing soil), and this frost action led to the mixing of older early Holocene Paleoindian artifacts with younger Altithermal age charcoal (Benedict, 2005). Postdepositional convolutions and wedge features may be an indication of frost action at Owl Cave, a volcanic blister on the Snake River Plain in Idaho (Dort, 1977). The stratigraphic sequence contains extinct animal fossils, such as mammoth and camel, as well as fluted points.

Paleolithic sites in France also contain evidence of periglacial activity. For example, at the well-known La Ferrassie rockshelter, solifluction during the last cold maximum of marine isotope stage 2 was similar to semi-desert-like periglacial conditions of today (Bertran et al., 2008). Solifluction appears to be the best explanation for geoarchaeological patterns at other French Paleolithic sites as well (Lenoble and Bertran, 2004; Lenoble et al., 2008).

In Russia, at Kostenki, an Upper Paleolithic locality on the Don River south of Moscow, heavily contorted and convoluted beds are an indication of solifluction or creep processes in deposits dating to around 35,000 ^{14}C BP (Holliday et al., 2007). The Diring Yuriakh Paleolithic site on a terrace of the Lena River contains permafrost sand wedges. Upper Paleolithic sites situated on terraces of the Chikoi River in Siberia east of Lake Baikal, such as Studenoe and Prisskovoe, contain cryoturbation features (Buvit et al., 2003; Buvit et al., 2011). At the late Pleistocene Berelekh mammoth site in northern Siberia, the bone bed truncates an ice wedge (Pitulko, 2010), while the Yana Rhinoceros Horn Site (Yana RHS) contains ice wedges that form a polygonal grid (Pitulko et al., 2004; Basilyan et al., 2011). The numerous ice wedges and slope deposits formed by solifluction at these sites document several cycles of freezing and thawing.

Glacial settings can lead to remarkable preservation of organic remains in archaeological and paleontological sites (Dixon et al., 2005). Melting glaciers and ice patches expose and release artifacts (Hare et al., 2012; Reckin, 2013). Perhaps the best known example is the preservation of Ötzi (the “Ice Man”) discovered in 1991 near a glaciated pass in the Alps (Baroni and Orombelli, 1996). In the southern Yukon, archaeological and paleontological specimens were discovered in thawing ice patches. Remains have been discovered in British Columbia along an ice ridge on a glacier. In the Rocky Mountains of Colorado, late Holocene remains of bison, mountain sheep, and cervids have been found in ice patches. Organic remains have also been preserved in Alaska. These include archaeological remains (Dixon et al., 2005) and Pleistocene animals preserved in ice or frozen ground (Guthrie, 1990).

Summary

Glacial settings are often the locations of ancient human activities. Archaeological sites may lie above glacial-related deposits, or they may be covered by drift. In addition, artifacts can be incorporated into glacial deposits. In short, glacial processes can preserve, modify, or destroy the evidence of human presence within a landscape. Rebound of the land resulting from the loading and unloading of large masses of ice is especially important in glaciated areas associated with glacial lake and coastal island settings. This situation prevails in landforms of proglacial and postglacial lakes, such as those associated with the southern margin of the Laurentide Ice Sheet. Additionally, in coastal areas, changes in relative sea level have had a dramatic impact on sediment deposition and landscape evolution. Sea-level fall associated with glacial advance first expanded coastal zones and created land bridges resulting in landscapes inhabitable by humans, then during warm periods, these areas are flooded, leading to significant impacts on site visibility and preservation. Periglacial processes, such as mixing and sorting of sediments by frost action or movement by soil flow, have the capacity to mix stratigraphic sequences or bury and preserve them. Glacial settings are critical to developing archaeological time frameworks, examining changing environmental conditions and landscape evolution, and integrating humans with past ecosystems.

Bibliography

Agassiz, L., 1840. *Études sur les glaciers*. Neuchâtel: Jent et Gassmann.

Al-Suwaidi, M., Ward, B. C., Wilson, M. C., Hebda, R. J., Nagorsen, D. W., Marshall, D., Ghaleb, B., Wigen, R. J., and Enkin, R. J., 2006. Late Wisconsinan Port Eliza Cave deposits and their implications for human coastal migration, Vancouver Island, Canada. *Geoarchaeology*, **21**(4), 307–332.

Ashley, G. M., Shaw, J., and Smith, N. D. (eds.), 1985. *Glacial Sedimentary Environments*. Tulsa: Society of Economic Paleontologists and Mineralogists.

Ashton, N. M., Cook, J., Lewis, S. G., and Rose, J. (eds.), 1992. *High Lodge: Excavations by G. De G. Sieveking, 1962–68, and J. Cook, 1988*. London: British Museum Press.

Bailey, G. N., and Flemming, N. C., 2008. Archaeology on the continental shelf: marine resources, submerged landscapes and underwater archaeology. *Quaternary Science Reviews*, **27** (23–24), 2153–2165.

Baroni, C., and Orombelli, G., 1996. The alpine “Iceman” and holocene climatic change. *Quaternary Research*, **46**(1), 78–83.

Basilyan, A. E., Anisimov, M. A., Nikolskiy, P. A., and Pitulko, V. V., 2011. Wooly mammoth mass accumulation next to the paleolithic yana RHS site, Arctic Siberia: its geology, age, and relation to past human activity. *Journal of Archaeological Science*, **38**(9), 2461–2474.

Benedict, J. B., 2005. Rethinking the fourth of July Valley site: a study in glacial and periglacial geoarchaeology. *Geoarchaeology*, **20**(8), 797–836.

Bennett, M. R., and Glasser, N. F., 2009. *Glacial Geology: Ice Sheets and Landforms*, 2nd edn. Chichester: Wiley-Blackwell.

Bertran, P., Caner, L., Langohr, R., Lemée, L., and d'Errico, F., 2008. Continental palaeoenvironments during MIS 2 and 3 in southwestern France: the la ferrassie rochshelter record. *Quaternary Science Reviews*, **27**(21–22), 2048–2063.

Bertran, P., Klaric, L., Lenoble, A., Masson, B., and Vallin, L., 2010. The impact of periglacial processes on Palaeolithic sites: the case of sorted patterned grounds. *Quaternary International*, **214**(1–2), 17–29.

Boyd, M., 2007. Paleoindian geoarchaeology of the Assiniboine delta of glacial Lake Agassiz. *Canadian Journal of Archaeology*, **31**(3: Supplement: Building a Contextual Milieu:

Interdisciplinary Modeling and Theoretical Perspectives from the SCAPE Project),198–221.

Buchner, A. P., and Pettipas, L. F., 1990. The early occupations of the Glacial Lake Agassiz basin in Manitoba: 11,500 to 7,700 B.P. In Lasca, N. P., and Donahue, J. (eds.), *Archaeological Geology of North America*. Boulder: Geological Society of America. Centennial Special Volume, Vol. 4.

Buvit, I., Waters, M. R., Konstantinov, M. V., and Konstantinov, A. V., 2003. Geoarchaeological investigations at Studenoe, an upper paleolithic site in the Transbaikal Region, Russia. *Geoarchaeology*, **18**(6), 649–673.

Buvit, I., Terry, K., Kolosov, V. K., and Konstantinov, M. V., 2011. The alluvial history and sedimentary record of the Priiskovoe site and its place in the paleolithic prehistory of Siberia. *Geoarchaeology*, **26**(5), 616–648.

Byers, D. S., 1954. Bull brook – a fluted point site in Ipswich, Massachusetts. *American Antiquity*, **19**(4), 343–351.

Curran, M. L., 1984. The Whipple Site and paleoindian tool assemblage variation: a comparison of intrasite structuring. *Archaeology of Eastern North America*, **12**, 5–40.

Davis, A. M., McAndrews, J. H., and Wallace, B. L., 1988. Paleoenvironment and the archaeological record at the L'Anse aux meadows site, Newfoundland. *Geoarchaeology*, **3**(1), 53–64.

Dixon, E. J., 2013. Late Pleistocene colonization of North America from Northeast Asia: new insights from large-scale paleogeographic reconstructions. *Quaternary International*, **285**, 57–67.

Dixon, E. J., Manley, W. F., and Lee, C. M., 2005. The emerging archaeology of glaciers and ice patches: examples from Alaska's Wrangell-St. Elias national park and preserve. *American Antiquity*, **70**(1), 129–143.

Dort, W., Jr., 1977. Synopsis of the geology of the Wasden Site, Eastern Snake River plain, Idaho. In Dort, W., Jr., and Miller, S. (eds.), *Archaeological Geology of Birch Creek Valley and the Eastern Snake River Plain, Idaho*. Idaho Falls: Robco Printing. First Annual Field Trip, Division of Archaeological Geology, Geological Society of America, pp. E/1–E/34.

Dyke, A. S., 2004. An outline of North American deglaciation with emphasis on central and northern Canada. In Ehlers, J., and Gibbard, P. L. (eds.), *Quaternary Glaciations: Extent and Chronology. Part II: North America*. Amsterdam: Elsevier, pp. 373–424.

Ehlers, J., 1996. *Quaternary and Glacial Geology* (Gibbard, P. L., English version). Chichester: John Wiley.

Ehlers, J., and Gibbard, P. L. (eds.), 2004a. *Quaternary Glaciations: Extent and Chronology. Part I: Europe*. Amsterdam: Elsevier.

Ehlers, J., and Gibbard, P. L. (eds.), 2004b. *Quaternary Glaciations: Extent and Chronology. Part II: North America*. Amsterdam: Elsevier.

Ehlers, J., and Gibbard, P. L. (eds.), 2004c. *Quaternary Glaciations: Extent and Chronology. Part III: South America, Asia, Africa, Australasia, and Antarctica*. Amsterdam: Elsevier.

Ehlers, J., and Gibbard, P. L. (eds.), 2011. *Quaternary Glaciations: Extent and Chronology: A Closer Look*. Amsterdam: Elsevier.

Fedje, D., Mackie, Q., Lacourse, T., and McLaren, D., 2011. Younger Dryas environments and archaeology on the Northwest Coast of North America. *Quaternary International*, **241**(2), 452–462.

Geikie, J., 1874. *The Great Ice Age, and its Relation to the Antiquity of Man*. New York: D. Appleton & Co.

Gramley, R. M., 1982. *The Vail Site: A Paleo-Indian Encampment in Maine*. Buffalo: Buffalo Museum of Science. Bulletin of the Buffalo Society of Natural Sciences, Vol. 30.

Guthrie, R. D., 1990. *Frozen Fauna of the Mammoth Steppe: The Story of Blue Babe*. Chicago: The University of Chicago Press.

Hambrey, M., 1994. *Glacial Environments*. Vancouver: UBC Press.

Hare, P. G., Thomas, C. D., Topper, T. N., and Gotthardt, R. M., 2012. The archaeology of Yukon ice patches: new artifacts, observations, and insights. *Arctic*, ***65***(Supplement 1: The Archaeology and Paleoecology of Alpine Ice Patches),118–135.

Hill, C. L., 2006a. Geologic framework and glaciation of the Western Area. In Ubelaker, D. H. (ed.), *Environment, Origins, and Population, volume 3, Handbook of North American Indians*. Washington, DC: Smithsonian Institution, pp. 47–60.

Hill, C. L., 2006b. Geologic framework and glaciation of the Central Area. In Ubelaker, D. H. (ed.), *Environment, Origins, and Population, volume 3, Handbook of North American Indians*. Washington, DC: Smithsonian Institution, pp. 67–80.

Hill, C. L., 2006c. Geologic framework and glaciation of the Eastern area. In Ubelaker, D. H. (ed.), *Environment, Origins, and Population, volume 3, Handbook of North American Indians*. Washington, DC: Smithsonian Institution, pp. 81–98.

Hill, C. L., 2006d. Stratigraphic and geochronologic contexts of mammoth (*Mammuthus*) and other Pleistocene fauna, upper Missouri Basin (northern Great Plains and Rocky Mountains), U.S.A. *Quaternary International*, **142–143**, 87–106.

Hill, C. L., 2007. Geoarchaeology and late glacial landscapes in the western Lake Superior region, central North America. *Geoarchaeology*, **22**(1), 15–47.

Hill, C. L., Rapp, G., and Jing, Z., 2011. Alluvial stratigraphy and geoarchaeology in the Big Fork River Valley, Minnesota: human response to late holocene environmental change. In Wilson, L. (ed.), *Human Interaction with the Geosphere: The Geoarchaeological Perspective*. London: Geological Society of London. Special Publication Volume, Vol. 352, pp. 109–124.

Holliday, V. T., and Mandel, R. D., 2006. Geoarchaeology of the plains, Southwest, and Great Lakes. In Ubelaker, D. H. (ed.), *Environment, Origins, and Population, volume 3, Handbook of North American Indians*. Washington, DC: Smithsonian Institution, pp. 23–46.

Holliday, V. T., Hoeffecker, J. F., Goldberg, P., MacPhail, R. I., Forman, S. L., Anikovich, M., and Sinitsyn, A., 2007. Geoarchaeology of the Kostenki-Borshevo Sites, Don River Valley, Russia. *Geoarchaeology*, **22**(2), 181–228.

Kellaway, G. A., 1971. Glaciation and the stones of Stonehenge. *Nature*, **233**(5314), 30–35.

Kelley, J. T., Belknap, D. F., and Claesson, S., 2010. Drowned coastal deposits with associated archaeological remains from a -sea-level "slowstand": Northwestern Gulf of Maine, USA. *Geology*, **38**(8), 695–698.

Kenady, S. M., Wilson, M. C., Schalk, R. F., and Mierendorf, R. R., 2011. Late Pleistocene butchered *Bison antiquus* from Ayer Pond, Orcas Island, Pacific Northwest: age confirmation and taphonomy. *Quaternary International*, **233**(2), 130–141.

Kooyman, B., Hills, L. V., McNeil, P., and Tolman, S., 2006. Late Pleistocene horse hunting at the Wally's Beach site (DhPg-8), Canada. *American Antiquity*, **71**(1), 101–121.

Kristensen, T. J., and Curtis, J. E., 2012. Late Holocene hunter-gatherers at L'Anse aux Meadows and the dynamics of bird and mammal hunting in Newfoundland. *Arctic Anthropology*, **49**(1), 68–87.

Lenoble, A., and Bertran, P., 2004. Fabric of Palaeolithic levels: methods and implications for site formation processes. *Journal of Archaeological Science*, **31**(4), 457–469.

Lenoble, A., Bertan, P., and Lacrampe, F., 2008. Solifluction-induced modifications of archaological levels: simulation based on experimental data from modern periglacial slope and application to French palaeolithic sites. *Journal of Archaeological Science*, **35**(1), 99–110.

Lovis, W. A., Arbogast, A. F., and Monaghan, G. W., 2012. *The Geoarchaeology of Lake Michigan Coastal Dunes*. East Lansing: Michigan State University Press.

Lundberg, J., and McFarlane, D. A., 2007. Pleistocene depositional history in a periglacial terrane: A 500 k.y. record from Kents Cavern, Devon, United Kingdom. *Geosphere*, **3**(4), 199–219.
McDonald, G. F., 1968. *Debert: A Paleo-Indian Site in Central Nova Scotia*. Ottawa: National Museum of Canada. Anthropology Papers, National Museum of Canada, Vol. 16.
Moir, J. R., 1924. Further discoveries of ancient flint implements at Cromer. *Nature*, **114**(2859), 242–243.
Phillips, B. A. M., and Hill, C. L., 2004. Deglaciation history and geomorphological character of the region between the Agassiz and Superior basins, associated with the 'Interlakes Composite' of Minnesota and Ontario. In Jackson, L. J., and Hinshelwood, A. (eds.), *The Late Palaeo-Indian Great Lakes: Geological and Archaeological Investigations of Late Pleistocene and Early Holocene Environments*. Gatineau: Canadian Museum of Civilization. Mercury Series Archaeology Paper, Vol. 165, pp. 275–301.
Pitulko, V. V., 2010. The Berelekh quest: a review of forty years of research in the mammoth graveyard in northeast Siberia. *Geoarchaeology*, **26**(1), 5–32.
Pitulko, V. V., Nilolsky, P. A., Girya, E. Y., Basilyan, A. E., Tumskoy, V. E., Koulakov, S. A., Astakhov, S. N., Pavlova, E. Y., and Anisimov, M. A., 2004. The Yana RHS Site: humans in the arctic before the last glacial maximum. *Science*, **303**(5654), 52–56.
Putnam, D. E., 1994. Vertical accretion of flood deposits and deeply stratified archaeological site formation in central Maine, USA. *Geoarchaeology*, **9**(6), 467–502.
Reckin, R., 2013. Ice patch archaeology in global perspective: archaeological discoveries from alpine ice patches worldwide and their relationship with paleoclimates. *Journal of World Prehistory*, **26**(4), 323–385.
Roe, D. A., 1993. Landmark sites of the British Palaeolithic. *Review of Archaeology*, **14**(2), 1–9.
Schweger, C., 1985. Geoarchaeology of northern regions: lessons from cryoturbation at Onion Portage, Alaska. In Stein, J. K., and Farrand, W. R. (eds.), *Archaeological Sediments in Context*. Orono, Maine: Center for the Study of Early Man, Institute for Quaternary Studies, University of Maine at Orono. Peopling of the Americas, Vol. 1, pp. 127–141.
Solberg, I.-L., Hansen, L., Rokoengen, K., Sveian, H., and Olsen, L., 2008. Deglaciation history and landscape development of fjord-valley deposits in Buvika, Mid-Norway. *Boreas*, **37**(2), 297–315.
Steffen, H., and Wu, P., 2011. Glacial isostatic adjustment in Fennoscandia – a review of data and modeling. *Journal of Geodynamics*, **52**(3–4), 169–204.
Stout, D., Apel, J., Commander, J., and Roberts, M., 2014. Late Acheulian technology and cognition at Boxgrove, UK. *Journal of Archaeological Science*, **41**, 576–590.
Sveian, H., 1997. Ice-marginal deposits and deglaciation chronology in Nord-Trøndelag and Fosen, central Norway. *Norges geologiske undersøkelse Bulletin [Geological Survey of Norway Bulletin]*, **433**, 52–53.
Sveian, H., and Olsen, L., 1984. En strandforskyvningskurve fra Verdalsøra, Nord-Trøndelag. *Norsk Geologisk Tidsskrift [Norwegian Journal of Geology]*, **64**(1), 27–38.
Thieme, D. W., 2003. Archaeological site formation in glaciated settings, New Jersey and Southern New York. In Cremeens, D. L., and Hart, J. P. (eds.), *Geoarchaeology of Landscapes in the Glaciated Northeas*. Albany: University of the State of New York. New York State Bulletin, Vol. 497, pp. 163–179.
Todisco, D., and Bhiry, N., 2008. Palaeoeskimo site burial by solifluction: periglacial geoarchaeology of the Tayara site (KbFk-7), Qikirtaq Island, Nunavik (Canada). *Geoarchaeology*, **23**(2), 177–211.
Ward, I., and Larcombe, P., 2008. Determining the preservation rating of submerged archaeology in the post-glacial southern North Sea: a first order geomorphological approach. *Environmental Archaeology*, **13**(1), 59–83.
Waters, M. R., Stafford, T. W., Jr., McDonald, H. G., Gustafson, G., Rasmussen, M., Cappellini, E., Olsen, J. V., Szklarczyk, D., Jensen, L. J., Gilbert, M. T. P., and Willerslev, E., 2011. Pre-Clovis mastodon hunting 13,800 years ago at the Manis site, Washington. *Science*, **334**(6054), 351–353.
Waters, M.R., Stafford, T.W., Jr. Kooyman, B., and Hill, L.V., 2015. Late Pleistocene horse and camel hunting at the southern margin of the ice-free corridor: Reassessing the age of Wally's Beach, Canada. Proceedings of the National Academy of Sciences, **112**(14), 49–61.
Williams-Thorpe, O., Aldiss, D., Rigby, I. J., and Thorpe, R. S., 1999. Geochemical provenancing of igneous glacial erratics from southern Britain, and implications for prehistoric stone implement distributions. *Geoarchaeology*, **14**(3), 209–246.
Wilson, M. C., Kenady, S. M., and Schalk, R. F., 2009. Late Pleistocene *Bison antiquus* from Orcas Island, Washington, and the biogeographic importance of an early postglacial land mammal dispersal corridor from the mainland to Vancouver Island. *Quaternary Research*, **71**(1), 49–61.
Wright, G. F., 1889. *The Ice Age in North America, and Its Bearings upon the Antiquity of Man*. New York: D. Appleton & Co.

Cross-references

Climatostratigraphy
Geomorphology
Landscape Archaeology
Oxygen Isotopes
Paleoenvironmental Reconstruction
Paleoshores (Lakes and Sea)
Radiocarbon Dating
Site Formation Processes
Submerged Continental Shelf Prehistory

GLASS

J. Victor Owen
Department of Geology, Saint Mary's University, Halifax, NS, Canada

Definition

Glass is an amorphous solid, typically brittle, and optically transparent or translucent.

Introduction

Glass can form naturally, notably by the rapid cooling (quenching) of lava (forming obsidian), or more rarely as a mineraloid lechatelierite when lightning strikes sand (forming fulgurites) and by bolide impacts (forming tektites). Man-made glasses traditionally have been made by heating silica-rich sand with suitable fluxes (e.g., Na, K, and/or Pb) and stabilizers (e.g., Ca). These materials, once mixed together for the purpose of making glass, are referred to as a glass batch. The clarity and color of man-made glass depend on the purity of the silica sand used in its manufacture, on the concentration and type of metals in the glass batch, and on the oxygen fugacity of the furnace atmosphere. The rapid cooling of molten glass creates stresses that can cause the object to crack. These stresses are dissipated by annealing the object in a lehr kiln, usually at temperatures between about 370 °C and 500 °C.

Although specialized types of glass (e.g., borosilicate glass) and glass-ceramic materials have been manufactured in recent years, most glass presently made is similar to historical glass that has been produced for centuries (e.g., soda-lime glass and alkali-lead glass).

Character of glass

The character of glass is perhaps best understood by contrasting its properties with those of crystalline solids and liquids. The molecules in crystalline solids are arranged in an orderly pattern: a crystal lattice. If heated to a sufficiently high temperature, the lattice breaks down, and the crystalline material begins to melt. There is thus an abrupt change – a first-order phase transition – in the physical properties (e.g., density) of the material.

In contrast to crystalline solids, liquids are a viscous medium. Viscosity is a measure of a liquid's resistance to flow, and the property depends on the composition (e.g., the silica content of silicate liquids) and temperature of the liquid. The viscosity of liquids generally increases as their temperature decreases, i.e., they become thicker and more resistant to flow. Ordinarily, a liquid will crystallize when it is cooled below the melting temperature of its solid counterpart, but if it is cooled very quickly (quenched or supercooled), it can solidify before nucleation and crystallization occur. Some liquids are characterized by slow nucleation kinetics at temperatures below their melting point. These are the glass formers, and silica-rich liquids are an example. When cooled at a standard cooling rate, the molecules in such glass formers remain disordered, and the solidified material is thus amorphous. The reasons for the sluggish nucleation rates of glass formers are not fully understood, so this topic remains an area of active research in condensed-matter physics (Angell, 2008).

The supercooling of glass-forming liquids to a glass state is referred to as vitrification, but it should be noted that ceramists use the same term to describe the generation of a melt phase in ceramic bodies being fired at high temperature. The transition between a liquid and its amorphous, solid counterpart, i.e., the glass transition, is characterized by a dramatic change in viscosity and by changes in heat capacity and thermal expansivity (Ojovan and Lee, 2006). At a temperature below that of the glass transition (T_g), the material is solid; above T_g, it is rubbery. Glass is indeed solid. The observation that very old pane glass can be relatively thick at its base has been misconstrued as evidence that glass is an extremely viscous liquid (Brill, 1962; Elliott, 1983). However, viscosity curves calculated for ancient and modern glass show that the flow of pane glass at room temperature would take an inordinate amount of time – about 10^{32} years, much longer than the age of the universe itself (Zanotto, 1998). Instead, differences in pane glass thickness have recently been interpreted as an artifact of the production process, whereby glass blowers would spin a glob (gather) of molten glass, which would tend to become progressively thinner toward its edge. This means of producing flat glass is known as the crown method. Once cut, the thicker edge of the glass would usually (but not invariably) be placed at the bottom of the window to render it stable (Brill, 2011).

The discovery of glass

Pliny the Elder, the Roman naturalist and historian, claimed that glass was accidentally discovered by Phoenician merchants while preparing a meal on the shore near the Belus River in Palestine (now the Na'aman River in northwestern Israel). Unable to find rocks suitable to support their cooking pots, they used blocks of natron (a flux, principally $Na_2CO_3{\cdot}10H_2O$ with subordinate sodium bicarbonate) instead. The heat from the fire caused the beach sand and natron to melt. The melt cooled quickly, forming glass. This anecdote has long been discredited by scholars because the temperatures produced by campfires are insufficient to cause the beach sand to melt, even in the presence of a flux such as natron. Instead, it has been proposed that the discovery of glass originated with the manufacture of early glazed ceramic wares such as faience (Bowman, 1991).

Exactly where and when glass was first made nevertheless remain open questions. There are several late Bronze Age sites in the eastern Mediterranean region where early glass has been recovered. These include Tell Brak (Syria; Oates et al., 1998), Amarna (Egypt; Petrie, 1926), and Knossos (Crete; Panagiotaki, 2008). However, glass was produced only at some sites, whereas at others, it was simply worked. This, together with the discovery of glass ingots from shipwrecks (e.g., Pulak, 2008) and evidence from the mid-fourteenth century BC, Amarna letters (Moran, 1992) testify to the extensive trade in raw glass around the Mediterranean at this time (Smirniou and Rehren, 2011).

Raw materials

Glass is made from a mixture of silica (quartz)-rich sand, fluxing agents (e.g., alkalis and/or lead), stabilizers (e.g., lime), and, where required, colorants, decolorants, and/or opacifiers. Its manufacture requires copious amounts of fuel. Historically, this was either wood or coal. Glass production centers therefore tended to be located where glass-grade silica sand and/or abundant fuel were locally available.

Silica sand

From a quality perspective, silica sand is the single most important ingredient of glass. Where glass-grade sand is not available, some historical glass producers crushed orthoquartzite. Ideally, glass-grade silica sand and orthoquartzite should contain >99 wt% SiO_2, i.e., should be nearly pure quartz. Impurities in quartz-rich sand and orthoquartzite are commonly dominated by stable, heavy minerals including various iron, titanium, and iron-titanium oxides such as magnetite, rutile (and other titania polymorphs), and ilmenite, respectively, along with apatite and zircon. Minor amounts of alkali feldspar and traces of various ferromagnesian minerals may also be present. If not removed from the sand before it is added to glass batches, these minor minerals will impart distinctive geochemical signatures to the glass that can be used to trace the source of silica used in its manufacture (e.g., Owen and Greenough, 2008).

Cullet

Cullet is scrap glass added to batches to facilitate melting. Commonly, between a quarter and half of a glass batch consists of this material. It usually is the same type of glass that is being produced, so it often simply represents the recycling of waste glass by the manufacturer. Some glassworks, however, advertised for scrap glass to be used as cullet (Starbuck, 1983). This material, being imported, must not be mistaken as a bona fide product of the glassworks where it is found.

Fluxes

Natron is thought to have been used as a flux in the production of some early glassware, but shortages in its supply led to a decline in its use in the glass industry of the Near East in the seventh to ninth centuries AD (Shortland et al., 2006). As a consequence, the use of alkali-rich plant ashes as a flux became increasingly important in the glass industry. Plant ashes, however, have been used in the Near East for millennia. Indeed, recent work (Tite et al., 2006) provided evidence of halophytic (salt tolerant) plants being used to make glass in this area since the fourth millennium BC. Fluxes influenced the melting behavior of glass batches. Ancient Egyptian and Roman soda-lime glass tends to have a limited range in compositions that approximate the eutectic (lowest melting point) on the $CaO–SiO_2–Na_2O$ phase diagram. Rehren (2000) hypothesized that the near-minimum melt composition of this glass was an artifact of *partial* batch melting, wherein the degree of melting of the glass batch, and hence the composition of the glass, was buffered either by a solid phase (e.g., pseudowollastonite, $CaSiO_3$) or the reactant surface of the crucible.

The Roman tradition of using ash from sodium-rich plants from coastal areas continued to parts of Europe (notably Venice) that could access traditional trade routes (Tait, 1991), but inland, ash from potassium-rich flora was used during the Medieval period. The development of the Medieval glass industry thus involved the use of novel batch ingredients. This, in turn, required the development of new technologies to ensure the successful production of potash-lime glass for which there was no precedent (Rehren, 2000).

Theophilus (c. 1100) described the making of glass batches from a mixture of beech wood ashes and sand in the ratio 2:1 and the fashioning of firing pots from white pottery clay (Presbyter, 1976). Huge amounts of wood were consumed by this industry. Smedley et al. (1998) reported that Theophilus's recipe would require 63 kg of beech wood to produce 1 kg of glass. These glasswares, known as Waldglas (forest glass), were produced in northern Europe between c. AD 1000 and 1700. They are characterized by potash-lime compositions with variable amounts of soda. In contrast to his partial batch melting model for ancient glass, Rehren (2000) accounted for the compositional diversity of European Medieval glass by proposing that Waldglas batches melted entirely, so their compositions were not confined to thermal minima.

Stabilizers

Stabilizers are used to make glass stronger and less soluble in water. Sodium- and potassium-rich glasses are susceptible to dissolution. The addition of calcium carbonate renders such glass relatively insoluble, and alumina is sometimes used to strengthen glass. Lead is also employed as a stabilizer, and its introduction to alkali glass batches produces a low-viscosity melt from which bubbles ("seeds") can easily escape. The resultant glass has a high refractive index, thereby giving it a brilliant luster. The invention of lead crystal is usually attributed to the English glassmaker George Ravenscroft (1632–1683).

When high levels of fluxing agent (Na_2O or K_2O) or insufficient stabilizer (CaO) are added to glass batches, the finished object can develop glass disease, a condition that poses serious challenges to conservators of historical glass artifacts. The deterioration is caused by humidity in the air (or soil in the case of buried contexts) that gradually hydrates the exterior and dissolves alkalis out of the glass, creating salt encrustations on the surface and eventually producing a web of cracks in the glass body (crizzling) that spreads, dulls, and darkens the glass and ultimately breaks up the object. Some buried or weathered vitreous materials (glass, glazes) become enriched in phosphate and lime and develop Liesegang rings (e.g., Freestone et al., 1985). Another kind of glass deterioration appears as iridescence, a multicolored effect caused by surficial weathering (Doménech-Carbó et al., 2006). Horizontal cracks form due to volume changes from the hydration of near-surface material, and this generates multiple microscopic laminations that continually break off as minute shiny flakes. Each of these sequential layers reflects incoming light, thereby creating interference colors that produce the iridescent appearance. A thin hydrated layer that evenly covers the glass surface can produce a light iridescence, but a thick buildup of multiple scaly laminae usually results in an opaque gold appearance.

In order to gauge the degree of corrosion in glass of various chemical compositions buried under alkaline soil conditions, the Ballidon glass burial experiment was begun in England in 1970 (Newton, 1985; McLoughin et al., 2006). Sequential openings over many years will reveal the kinds and extent of deterioration to glass specimens designed to replicate the formulas used in Roman, Medieval, and seventeenth-century products.

Colorants

Small amounts of metallic and nonmetallic elements impart color to glass. Chief among the metals is iron which, in its ferrous (Fe^{2+}) state, renders glass a bluish-green tint. Ferric (Fe^{3+}) iron gives glass a yellowish-green color. Cobalt and copper have been used since the ancient times to produce blue glass. Amber glass is produced through the use of sulfur and iron, and red glass can be made using gold chloride. Uranium-bearing glass is a bright yellowish green.

Decolorants

In order to produce relatively colorless, transparent glass, a decolorant such as manganese dioxide (the mineral pyrolusite) can be added to the glass batch. Indeed, "pyrolusite" is derived from the Greek words for "fire" and "wash." Other decolorants include antimony (Henderson, 2000), cobalt oxide, and selenium. Decolorants produce complimentary colors to the green tints associated with iron, thereby chromatically neutralizing them.

Where they are used in excess, decolorants can cause glass to become cloudy or dark (Vose, 1996). Chemical analysis nevertheless shows that historical black glass can have comparatively low silica contents and high alumina and iron as well as manganese contents. This suggests that it was made using relatively impure (e.g., quartz-poor, feldspar-, and iron-bearing mineral-rich) sand.

Opacifiers

Opacifiers are used to render opaque the medium (e.g., glass, glazes) to which they are added. A wide variety of compounds serve as opacifiers, but all are relatively refractory, have a high refractive index, and are added to glass (and glaze) batches as finely ground grains. They include tin oxide, calcium antimonite, and calcium phosphate (Henderson, 2000).

Glass-working techniques

Ancient glass-working techniques included core forming, rod forming, slumping, casting, and blowing (free blowing and mold [mould] blowing). Core forming involves shaping the glass around a core. Traditionally, the core was thought to have exclusively been formed in sand, but recent work suggests that coal, dung, or crushed quartz was also used. Once formed, the core was attached to a metal rod, heated, and then dipped into molten glass. Irregularities in the surface of the glass were smoothed out by rolling the glass-coated core (marvering) over a smooth surface. Decoration was often applied as trails of glass, which commonly were combed into various patterns while still molten. The core was removed afterward. A variation of this process known as rod forming was used to make slender vessels and jewelry. It involved applying a separating agent to a metal rod, which was then coated by threads of glass.

Slumping involved heating a piece of flat glass until it softened and descended due to the pull of gravity over a refractory, convex, or concave form (mold). This differs from casting, whereby molten glass was poured into molds. The forms into which the molten glass was poured included both open molds and molds made by the lost-wax process, in which a wax model of the object to be cast was enclosed by clay and heated to remove the wax leaving a void which was then replaced within the mold by molten glass.

The technique of blowing glass originated in the eastern Mediterranean region, possibly along the Syro-Phoenician coast, during the first century BC (e.g., Frank, 1982) and was subsequently refined by the Romans. Free blowing, then as now, involved the use of a blowpipe to inflate a gather of molten glass, which was then shaped into its desired form. A contemporary variant known as the dip-overlay method was used by the Romans to produce cameo glass. This involved dipping a bubble of colored glass into a molten white glass and then blowing both together into the desired form. Finally, parts of the white glass were carefully carved away, leaving a pattern in relief set against the colored glass background. The Portland Vase (c. AD 5–25) is thought to have been made by this method.

In mold blowing, a gather of glass is inflated into a mold. Two- and three-piece molds are most commonly used; the edges of these molds leave a telltale thin ridge (seam lines) on glass objects, which included everything from bottles to tableware. A variant of this technique known as pressing involves the use of a plunger to compress molten glass that has been poured into a mold. This technique, developed in the United States in the 1820s, was perfected by the Boston and Sandwich Glass Co. (1826–1888) of Massachusetts.

The mass production of bottles began in the early 1900s, when M. J. Owens introduced the Owens Bottle Machine. This device used a piston pump to suck molten glass into a mold to measure the appropriate volume of glass for particular bottles. The action of the pump was then reversed to force the molten glass into a bottle mold. Up to four bottles per second could be produced by Owens's machines (Lockhart et al., 2010).

The production of sizeable sheets of flat glass for use as windowpanes presented glassmakers with a special challenge. Flat glass has been produced since the ancient times. It was produced either by rolling molten glass on a metal table or by spinning a large bubble of glass that had been transferred from a blowpipe to a rod (called a punty or pontil). The resulting glass disk, known as a rondelle, could be up to about 1 m in diameter; once formed, it was annealed to prevent cracks upon cooling too quickly, and then it was cut into smaller pieces for use as windowpanes. The "bull's eye" mark at the center of the disk is a signature of this type of flat glass. As noted earlier, flat glass produced by this method is known as crown glass. Crown glass was produced on a commercial scale at least until the middle of the nineteenth century.

Larger sheets of flat glass were produced by blowing a long cylinder of glass, which was then cut longitudinally, reheated, and opened up to form a flattened sheet up to 2 m square. This technique, called broad glass manufacture, yields glass that tends to be uneven in thickness, can contain abundant bubbles, and can be scored with tool marks from the metal rods used to flatten it (Phillips, 1981). A mechanized version of this technique was introduced in the early 1900s. It was supplanted first by the vertical draw (Fourcault) process, whereby a leader was pulled upward from a vat of molten glass, and subsequently by the float method developed in the 1950s by Pilkington Brothers Ltd. (Barker, 1977). Float glass is produced by pouring molten glass over a surface of molten tin.

A practical handbook reviewing the manufacture of glass at the beginning of the last century was published by Bastow (1920). More recently, Janssens (2013) reviewed various aspects of glass, its raw materials, its production, the composition of both ancient and more recent glass, the diverse methods of analyzing it, the composition and means of analyzing it, and the types of information these analytical data can provide to archaeologists.

Interpretation of archaeological glass from production centers

Glass is ubiquitous in the archaeological record, and much is known about its production over the centuries. As with archaeological ceramics, emphasis has been placed on excavating glass from production centers. The reason for this is twofold. First, careful excavation of glasswork sites can shed light on historical glass technologies. This can be accomplished by documenting kiln/furnace configurations and through the discovery of unprocessed raw materials, glass-working tools, and specimens of worked glass. Second, the compositional analysis of worked glass from production centers provides baseline data for reconstructing trade routes and sourcing glass artifacts found elsewhere. Caution must be exercised when interpreting such data, because at some sites, glass was worked but not actually manufactured from raw materials, and at others, use was made of imported cullet, which would skew the chemistry of glass produced from raw materials alone at the site. Glass-on-crucible (melting pot) samples provide definitive evidence for the local production of glass, and a priority should be placed on analyzing such material. Again, caution is advised when interpreting the significance of glass adhered to kiln materials, as in some instances, such glass can represent a melt phase originating from the kiln material itself (Owen and Culhane, 2005).

Workers migrating from one production center to another carried technical knowledge of the glass industry with them. Thus, the forms, types, and compositions of glass produced in one area gradually spread elsewhere. For example, the characteristic glass forms produced in southern New Jersey starting in the eighteenth century subsequently appeared in glassworks in upstate New York and elsewhere (White, 1950). These wares can be so similar that their distinction must be based on analytical data, including trace elements. Even these data can fail to provide a definitive means of distinguishing wares produced at competing glassworks where similar batches containing sand and other ingredients from a common source were employed.

Bibliography

Angell, C. A., 2008. Glass-formers and viscous liquid slowdown since David Turnbull: enduring puzzles and new twists. *Materials Research Society Bulletin*, **33**(5), 544–555.

Barker, T. C., 1977. *The Glassmakers. Pilkington: The Rise of an International Company, 1826–1976*. London: Weidenfeld and Niccolson.

Bastow, H., 1920. *American Glass Practice; A Practical Book Devoted to Actual Glass Factory Conditions*. Pittsburgh: The Glassworker.

Bowman, S. (ed.), 1991. *Science and the Past*. Toronto: University of Toronto Press.

Brill, R. H., 1962. A note on the scientist's definition of glass. *Journal of Glass Studies*, **4**, 127–138.

Brill, R., 2011. Does glass flow? http://www.cmog.org/article/does-glass-flow

Doménech-Carbó, M.-T., Doménech-Carbó, A., Osete-Cortina, L., and Saurí-Peris, M.-C., 2006. A study on corrosion processes of archaeological glass from the Valencian region (Spain) and its consolidation treatment. *Microchimica Acta*, **154**(1–2), 123–142.

Elliott, S. R., 1983. *Physics of Amorphous Materials*. London: Longman.

Frank, S., 1982. *Glass and Archaeology*. London: Academic.

Freestone, I. C., Meeks, N. D., and Middleton, A. P., 1985. Retention of phosphate in buried ceramics: an electron microbeam approach. *Archaeometry*, **27**(2), 161–177.

Henderson, J., 2000. *The Science and Archaeology of Materials. An Investigation of Inorganic Materials*. London: Routledge.

Janssens, K. H. A. (ed.), 2013. *Modern Methods for Analysing Archaeological and Historical Glass*. Chichester: John Wiley and Sons.

Lockhart, B., Schulz, P., Serr, C., and Lindsey, B., 2010. The dating game – the Owens Bottle Co. *Bottles and Extras*, **21**(1), 50–62.

McLoughin, S. D., Hand, R. J., Hyatt, N. C., Lee, W. E., Notingher, I., McPhail, D. S., and Henderson, J., 2006. The long term

corrosion of glasses: analytical results after 32 years of burial at Ballidon. *Glass Technology*, **47**(3), 59–67.
Moran, W. L., 1992. *The Amarna Letters*. Baltimore: Johns Hopkins University Press.
Newton, R. G., 1985. The Ballidon glass burial. *Glass Technology*, **26**(6), 293–295.
Oates, D., Oates, J., and McDonald, H., 1998. *Excavations at Tell Brak, Vol. 1. The Mitanni and Old Babylonian Periods*. Cambridge: McDonald Institute.
Ojovan, M. I., and Lee, W. E., 2006. Topologically disordered systems at the glass transition. *Journal of Physics: Condensed Matter*, **18**(50), 11507–11520.
Owen, J. V., and Culhane, P., 2005. Pyrometamorphism of 19th-century kiln artifacts from Caledonia Springs, Ontario, Canada. *Geoarchaeology*, **20**(8), 777–796.
Owen, J. V., and Greenough, J. D., 2008. Influence of Potsdam sandstone on the trace element signatures of some 19th century American and Canadian glass: Redwood, Redford, Mallorytown, and Como-Hudson. *Geoarchaeology*, **23**(5), 587–607.
Panagiotaki, M., 2008. The technological development of Aegean vitreous materials in the Bronze Age. In Jackson, C. M., and Wager, E. C. (eds.), *Vitreous Materials in the Late Bronze Age Aegean: A Window to the East Mediterranean World*. Oxford: Oxbow Books. Sheffield Studies in Aegean Archaeology, Vol. 9, pp. 34–63.
Petrie, W. M. F., 1926. Glass in the early ages. *Journal of the Society of Glass Technology*, **10**, 229–234.
Phillips, P., 1981. *The Encyclopedia of Glass*. New York: Crown Publishers.
Presbyter, T., 1976. *On Divers Arts: The Treatise of Theophilus*. Chicago: University of Chicago Press.
Pulak, C., 2008. The Uluburun shipwreck and Late Bronze Age trade. In Aruz, J., Benzel, K., and Evans, J. M. (eds.), *Beyond Babylon: Art, Trade, and Diplomacy in the Second Millennium B.C*. New York: The Metropolitan Museum of Art, pp. 289–310.
Rehren, T., 2000. Rationales in Old World base glass compositions. *Journal of Archaeological Science*, **27**(12), 1225–1234.
Shortland, A., Schachner, L., Freestone, I., and Tite, M., 2006. Natron as a flux in the early vitreous materials industry: sources, beginnings and reasons for decline. *Journal of Archaeological Science*, **33**(4), 521–530.
Smedley, J. W., Jackson, C. M., and Booth, C. A., 1998. Back to the roots: the raw materials, glass recipes and glassmaking practices of Theophilus. In McCray, P. (ed.), *The Prehistory and History of Glassmaking Technology*. Westerville: American Ceramic Society. Ceramics and Civilization, Vol. 8, pp. 145–165.
Smirniou, M., and Rehren, T., 2011. Direct evidence of primary glass production in Late Bronze Age Amarna, Egypt. *Archaeometry*, **53**(1), 58–80.
Starbuck, D. R., 1983. The New England glassworks in Temple, New Hampshire. *The Journal of the Society for Industrial Archaeology*, **9**(1), 45–64.
Tait, H., 1991. *Five Thousand Years of Glass*. London: British Museum Press.
Tite, M. S., Shortland, A., Maniatis, Y., Kavoussanaki, D., and Harris, S. A., 2006. The composition of the soda-rich and mixed alkali plant ashes used in the production of glass. *Journal of Archaeological Science*, **33**(9), 1284–1292.
Vose, R. H., 1996. *A Collector's Guide to Antique Glass*. London: Leopard.
White, H. H., 1950. Migrations of early glassworkers. In *The Antiques Book*. New York: Bonanza Books, pp. 161–168.
Zanotto, E. D., 1998. Do cathedral glasses flow? *American Journal of Physics*, **66**(5), 392–395.

GRAIN SIZE ANALYSIS

Gloria I. López
Luminescence Laboratory, Centro Nacional de Investigación sobre la Evolución Humana CENIEH, Burgos, Spain
Leon Recanati Institute for Maritime Studies, University of Haifa, Mt. Carmel, Haifa, Israel

Synonyms

Granulometry; Particle size analysis

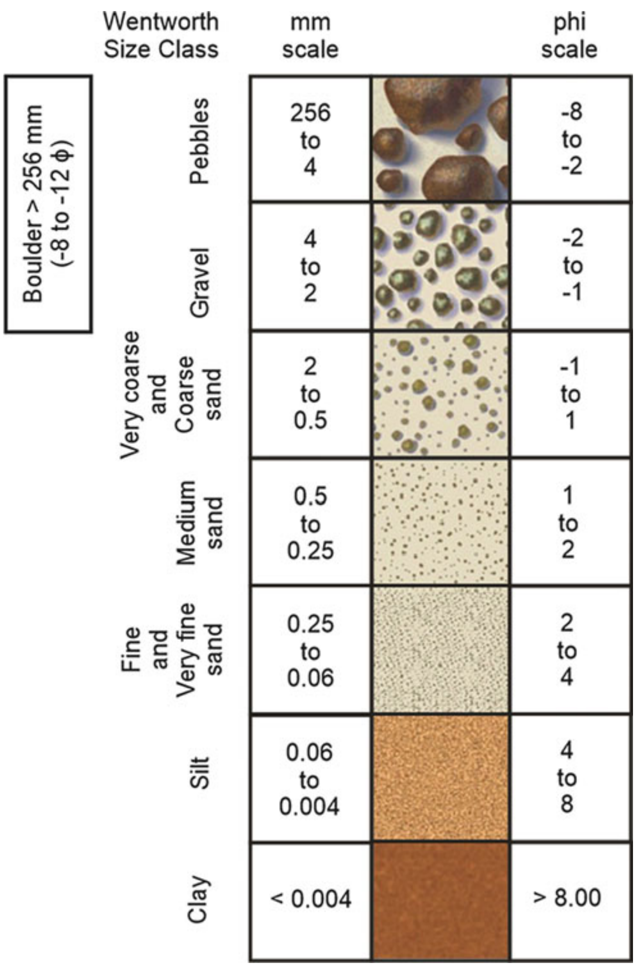
Definition

Grain size analysis is an analytical technique typically conducted within the earth sciences and implemented as a routine laboratory study. Other disciplines, such as archaeology and geoarchaeology, also use it regularly. It is a sedimentological analysis carried out in order to determine the size of the different particles that constitute a particular unconsolidated sedimentary deposit, sedimentary rock, archaeological locus, or soil unit. The main goal of this procedure is to determine the type of environment and energy associated with the transport mechanism at the time of deposition; this is done by inference from the sizes of the sediment particles analyzed and their distributions.

Introduction

Granulometry is a basic analytical technique that has wide applications within the earth and archaeological sciences. Particle or grain size is a fundamental attribute or physical property of particulate samples or sediments and sedimentary rocks (Friedman and Sanders, 1978; Folk, 1980). Much can be determined from an analysis of not only the size of clastic or detrital (inorganic), bioclastic (organic), or chemical particles but also of the overall size distribution, size fraction percentages, textural maturity of the sediment or sorting, surface texture attributes of a particle, and sphericity/angularity and shape of a particle (Krumbein and Sloss, 1963; Syvitski, 2007). Several sediment, soil, or material properties are directly influenced by the size of its particles, as well as their shape (form, roundness, and surface texture of the grains) and fabric (grain-to-grain interrelation and grain orientation), such as texture and appearance, density, porosity, and permeability.

The size of particles is directly dependent on the type of environmental setting, transporting agent, length and time during transport, and depositional conditions, and hence it possesses significant utility as an environmental proxy (McManus, 1988; Stanley-Wood and Lines, 1992). Grain size is related to a multitude of external factors acting on a local or regional scale. For example, in the coastal and marine setting, grain size is related to the bathymetry and geometry of the basin, nutrient regime, biogeochemical oceanography, coastal processes, net sedimentary



Grain Size Analysis, Figure 1 Diagram showing the different ranges of particle size, based on the Udden-Wentworth and Ø grain size scales for siliciclastic sediments (based on Wentworth, 1922; Krumbein and Sloss, 1963).

inputs from land sources, and outputs. The study of these particles can elucidate their provenance (source materials), the various processes they may have endured during their transport (by air, land, or water), their final depositional environment, their final burial setting (how much energy was present at that time; e.g., from waves or currents), and other physical and chemical factors.

Traditionally, sediments were divided into three principal categories: gravel, sand, and mud. The latter was further divided into silt and clay, mostly based on mineralogical distinction rather than (hydro-)dynamic properties. Since the early 1900s, standardization of such size ranges has been defined (Figure 1) based upon different grade scales constrained by particle size limits or range boundaries. The size of the particles is based on their nominal diameter, traditionally reported in millimeters (mm), micrometers (μm), or phi (Ø) units. The Wentworth or Udden-Wentworth scale (Udden, 1914; Wentworth, 1922) divides the size ranges into textural classes with specific terminology, from boulders (>200 mm) to clay (<0.004 mm). It is a geometric scale in which each size limit is 1/2 or twice the millimeter value of the next (Figure 1). The Krumbein Ø scale (Krumbein and Sloss, 1963) is a logarithmic scale modified from the Udden-Wentworth one and based on conveniently calculated round values, to avoid dealing with mm fractions (Figure 1). Classification of detrital sediments is based upon the quantification of, or relationship between, the proportions/percentages/ratios of different particle size fractions or textural classes within a mixed sediment (Shepard, 1954; Folk, 1980), as seen in Figure 2.

Grain size analysis is often part of the basic, initial set of analytical laboratory procedures scientists conduct upon sediment/soil samples and/or sediment cores recently collected in the field. The purpose of such analysis is to (1) obtain a deeper understanding of paleo-environmental features or modern environmental impacts, (2) reconstruct past sedimentary transport histories, depositional conditions, or sediment provenance, or (3) analyze in detail a catastrophic event, such as a tsunami or hurricane deposit, for example.

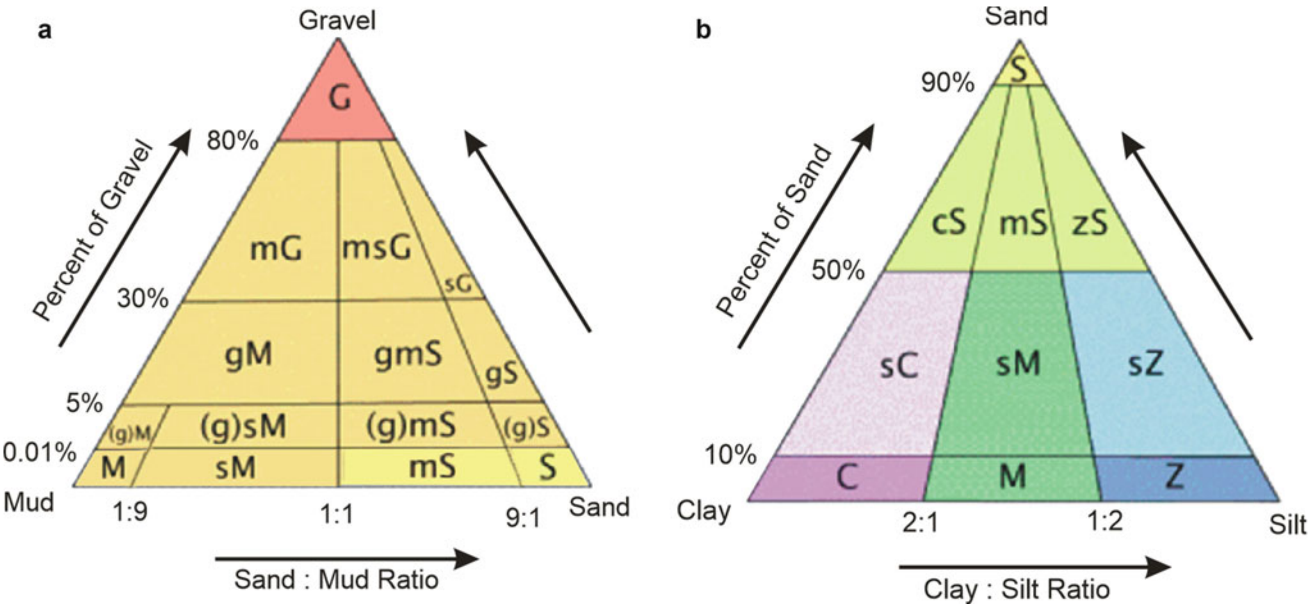
Depending on the thickness and areal extent of the sedimentary layer, unit, deposit, or archaeological locus, scientists collect one or multiple samples within that unit in order to obtain representative material and, with sufficient sampling, a more accurate statistical result. The resulting grain size analyses of samples collected from a single unit are averaged in order to obtain the overall particle size distribution.

Several analytical methodologies can be applied in the study of granulometry and the distribution of particle sizes within a sample or specific material (Table 1). These vary in terms of applicability, technique, apparatus, and cost (Table 2). Nonetheless, the method selected would depend on the range of particle sizes, the degree of consolidation of the material, and the purpose of the analysis. Traditional analyses include counting (individual clasts, manually), sieving, and settling, for gravelly, sandy, and muddy materials, respectively. Modern analyses (Table 1) have used the same analytical principles (count, sieve, and settle), however, the methodologies are much improved today due to better instrumentation and automatization (Table 2), including laser diffraction and imaging techniques (e.g., spectrometry), without discarding traditional sieving and settling (hydrometer and pipette analysis) methodologies (Syvitski, 2007).

Contextual granulometry

Granulometry in geoarchaeology

Granulometry can be considered a perfect example of geoarchaeological research in which the application of an earth sciences technique is used to understand aspects of the archaeological record. For example, in order to obtain a better understanding of the composition of a locus or stratigraphic unit, grain size analyses would be a basic parameter to estimate in order to differentiate the



Grain Size Analysis, Figure 2 Ternary diagrams (**a** and **b**) showing Folk's classification system of sediments: textural terminology conceived as a graphical representation of the relative proportions of different grain size typologies, resulting in 21 major categories (Folk, 1980). The abbreviations are: *G* gravel, *g* gravelly, *(g)* slightly gravelly, *S* sand, *s* sandy, *M* mud, *m* muddy, *Z* silt, *z* silty, *C* clay, *c* clayey.

Grain Size Analysis, Table 1 Commonly used grain size characterization techniques and the particle size ranges (from nanometers, nm, to millimeters, mm) with which they function optimally. The upper and lower range limits are only a guide, as these limits may vary from one application or instrument to another

Particle Size Range	0.1 nm	1 nm	10 nm	100 nm	1 µm	10 µm	100 µm	1 mm	10 mm
Applicable Analytical Technique									
Sieving									
Laser Diffraction									
Settling									
Dynamic Light Scattering									

Grain Size Analysis, Table 2 Suitability of commonly used grain size characterization techniques: an increasing number of stars indicates a higher degree of appropriateness for each indicator

Analytical Technique	Rapidity of the Process	Resolution	Dynamic range	Sampling	Wet	Dry
Sieving	*	*	*	*	*	*
Laser diffraction	***	**	****	***	*	*
Settling	*	**	**	**	*	
Dynamic light scattering	***	**	***	**	*	

matrix from the clasts/aggregates (*geological terms*) or inclusions (*archaeological term*), within the same locus/unit and/or across loci/units. This information enables a more precise understanding of particles that might be related to natural deposition versus those deriving from an anthropogenic origin – as some anthropogenic deposits have granulometric characteristics that cannot be compared to any natural pattern since they derive exclusively from artificial behaviors. An example is the differentiation between naturally-derived and anthropogenically-produced submerged sedimentary units found within the same archaeologically-rich coastal region of Caesarea Maritima, Israel (Reinhardt et al., 2006). Detailed analysis of *Glycymeris* spp. (saltwater clam) bio-clast distributions found at different stratigraphic intervals indicated two distinct naturally marine-derived tsunami phases; these were compared to an anthropogenically induced and/or mixed ballast and pottery layer amid naturally occurring medium sand-sized siliciclastic sedimentation related to normal marine and winter storm conditions. However, subsequent reinterpretations by some of the authors, based primarily on particle size distributions (diameters <2 mm) and several sedimentary textural and structural features, now suggest a tsunami origin for the previously identified anthropogenic layer (Morhange et al., 2014). This is an example of the complexity involved in weighting one analytical proxy more than others, or the difficulty of identifying and characterizing natural from anthropogenic units in complex environmental settings and reworked archaeological deposits.

Paleoenvironmental reconstruction

One of the goals of geoarchaeological research is to understand previous natural and anthropogenic events that took place within an archaeological context, either happening in sequence or ongoing intermittently. Based on such information, the environmental history of a site can be reconstructed from its beginnings. As a primary analytical technique, particle size analysis should always be accompanied by other basic analyses that have the potential to enhance comprehension of a targeted locus or sedimentary unit within the archaeological context. Examples of such other proxies are micropaleontology and isotope and chemical analyses. The combined use of several analytical laboratory procedures increases the likelihood of obtaining data useful in elucidating the depositional context as a whole, and with decreasing margin of error. Underwater archaeological sites, and especially those situated along coastal areas, are among the more complex settings within which to reconstruct the stratigraphic succession of ancient environments. This is due not only to the submerged conditions, but also to the highly dynamic processes occurring therein, including sea-level changes, severe storms, extreme events such as tsunamis, littoral currents, and sediment movement, etc. In conjunction with these, prolonged and heavy human occupation of the (ancient) coastline adds to the complexity of the setting. Nonetheless, well-documented reconstructions of the lateral and/or vertical progression of environments due to continuous environmental evolution, abrupt natural changes, and man-made constructions can be seen throughout ancient coastlines. Examples from the Mediterranean include the reconstruction of the now submerged ancient city and port of Alexandria on the Nile Delta, Egypt (Mostafa et al., 2000), the reconstruction of the harbor complex of Caesarea Maritima, Israel – the largest constructed artificial harbor in the Mediterranean (Reinhardt et al., 2006), and the understanding of the destruction of ancient Palaikastro in Crete following the great eruption of Santorini in the Late Bronze Age (Bruins et al., 2008).

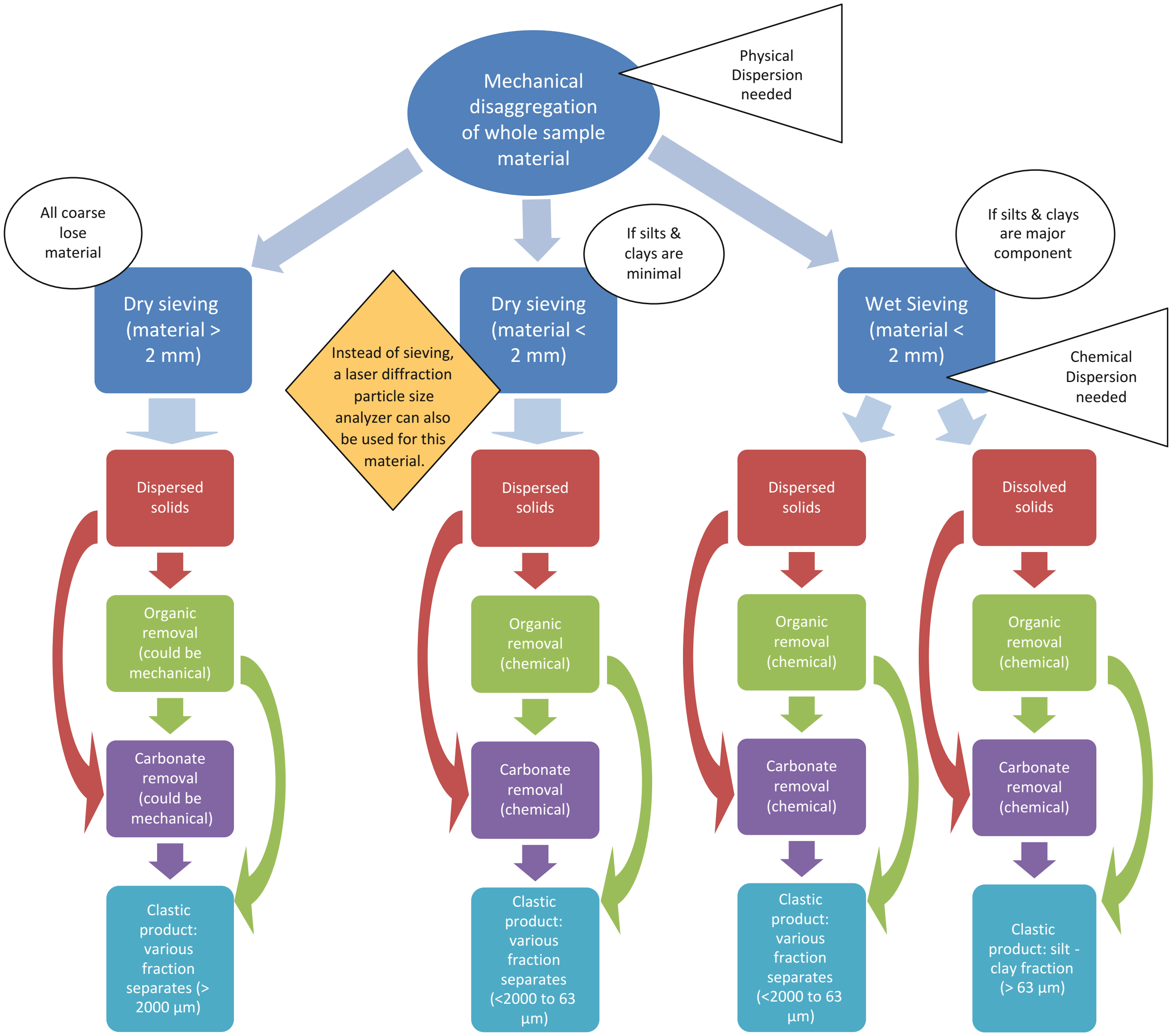
Analytical procedures and particle sizing techniques

One of the particularities of grain size analysis is the importance of estimating correctly the different size fractions that constitute the ensemble of the material being analyzed. In theory, each particle constituting the sample is to be analyzed individually, and the final result is the combination of all the individual measurements. Particles are complex three-dimensional objects with specific lengths, widths, and thicknesses, however (Folk, 1980; Stanley-Wood and Lines, 1992). Only perfect spheres can be completely described by a single number, i.e., their radius or diameter. So, in order to simplify the measurement process, particles are most commonly conceptualized as one-dimensional spheres rather than three-dimensional objects with irregular shapes. A cylinder with X length and Y diameter can be equivalent to a sphere of Z diameter that has the same volume as the cylinder. This is called the Concept of Equivalent Spheres (Jennings and Parslow, 1988). This concept can be applied to a number of different measuring properties of a particle, such as maximum and minimum diameter, surface area, volume, or weight. Based on this concept of equivalent spheres, sedimentation rates can be calculated, and simple things such as sieve aperture sizes can be specified (Folk, 1980; McManus, 1988).

If a sample is measured using different technical means, the results of each technique may not be equivalent because different apparatuses measure different parameters of the equivalent spheres. Therefore, consistency and comparability must be maintained. Grain size analyses can be performed by various means, in both dry and wet settings, depending on the type of material and its major constituent fraction. The coarse fraction of the sediment (>0.063 mm) is commonly separated through dry sieving, whereas the finer sediment can be isolated by settling or sedimentation (using a hydrometer) or using laser diffraction (see Tables 1 and 2). Preparation of the sample is also a crucial point in the determination of a credible and accurate grain size measurement, and hence the importance of the objective of the study. If the target material is clastic, removal of other allochthonous materials is compulsory (e.g., organics, carbonates, oxides, salts, etc.) to avoid erroneous measurements and vice versa (Figure 3).

Sieving analysis

Sieving is the most basic of the particle sizing techniques. It consists of having the sediment pass through (by agitation) a series of stacked sieve meshes with defined opening sizes. Each sieve catches the size fraction that is larger than its mesh size, so that the successive



Grain Size Analysis, Figure 3 Flow diagram generalizing the steps taken when dealing with particle size analyses. Steps may be bypassed or more procedures may be added depending on the amount, type, condition, and size distribution (gradation) of each sample. For example, iron oxide removal with chemical agents may be needed in some samples in lieu of organic matter or carbonate removal. The same is true for the removal of any soluble salts. Chemical dispersion with appropriate dispersing chemicals such as Na-hexametaphosphate, Na_2PO_7, or NaOH (among others) is needed after removal of cementing and flocculating agents, mostly when dealing with silt and clay materials. The number of fractions of clastic "end product" would depend on the number of sieves used during the sieving process. Most laser diffraction particle size analyzers are specialized in a particular range of size fractions in order to avoid obstruction and/or laser errors, e.g., sand fraction (maximum particle size of 2,000 µm), or fine fraction (maximum particle size of 200 µm).

sieves break up the sample into decreasing size fractions. The sediment fraction retained in each sieve is weighed in order to obtain its percentage relative to the whole sample. This technique can be used under dry or wet conditions.

The advantages of sieving are that it is cheap and user friendly, useful when dealing with very coarse samples, and the physical separation of the sample is the end result. Its limitations are its low resolution and precision, that dry particles smaller than 50 µm or cohesive materials are very difficult to separate using this technique, and that results are influenced by the operator and the duration of agitation/shaking used, i.e., the technique itself (Krumbein and Sloss, 1963; Folk, 1980).

Sedimentation or settling

Sedimentation is the oldest of the techniques used in particle size analysis. It measures the rate of sedimentation of particles suspended in a liquid. Its advantages include its relatively low cost, and its ease of applicability to soils or very fine sediments (for which it is the traditional method). Its limitations are that it is useful only for a limited range of particle sizes, that it is not useful for sediment <5 μm, and that it is extremely sensitive to particle shape (geometry) (Jennings and Parslow, 1988; Stanley-Wood and Lines, 1992).

Laser diffraction

Laser diffraction measures the angular dependence of laser light scattered by an ensemble of particles. Its advantages are that it can handle a very wide range of particle sizes (from <100 nm to ~2–3 mm), that measurements can be made rapidly and thus large numbers of samples can be processed, and that results are accurate and repeatable (Syvitski, 2007).

Laser diffraction measurements provide particle size distributions with great detail. This enhancement in technical size measurement has greatly improved the ability to differentiate and compare different environments, and sometimes even better understand their dynamics.

When using a laser diffraction particle size analyzer, sediment can be run dry or wet. If wet, however, it is advised to pour out as much water as possible from the container to minimize errors. In either case, homogenizing and dispersing the sample prior to insertion into the machine is always a must, in order to analyze a truly representative portion of the sample.

The limitations of laser diffraction include that it is not suitable for very coarse or nanomaterials. It is a medium resolution technique and is applied to the whole (ensemble) sample.

Dynamic light scattering

Dynamic light scattering measures scattered light intensity variations due to Brownian motion of particles in suspension within a liquid. Its advantages are that its dynamic range is well suited to nanomaterials (<1 nm to 1 μm), its measurement speed is rapid so that it can handle larger numbers of samples, and its results are accurate and repeatable. Its limitations include the inability to analyze dense materials, and its medium resolution (Syvitski, 2007).

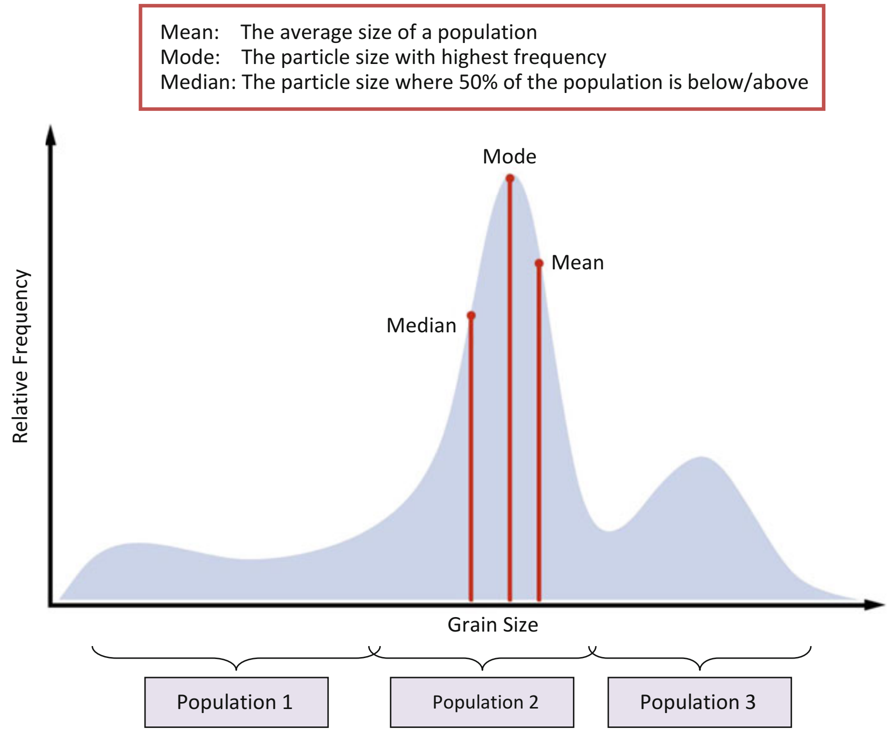
Particle size distributions

In nature, sediments do not consist of only one kind of particle, but rather an amalgamation of various particle sizes, and hence it is logical to consider grain size as a continuous variable. Only perfectly monodispersed samples possess particles of exactly the same size, for example, highly sorted sand winnowed through hydrodynamic processes. Most natural samples contain a range, or distribution, of different particle sizes and shapes.

As a result of manual or instrumental measurement of grain size, a size frequency spectrum is obtained. Such a spectrum is determined by the count of grains, weight, or volume percent of a particular particle fraction within a specific size interval. The resulting spectrum can be deployed as a distribution of grain sizes based on the relative frequency of their number per size fraction (Figure 4). The most common graphic depiction used to represent the different grain sizes within a sample consists of a statistical distribution encompassing all resulting fractions based on their relative frequency (quantity or volume). Two common representations are used routinely: relative frequency and cumulative distribution curves (e.g., Figure 4). The different shapes of the relative frequency distribution curve can be interpreted as how well sorted the sample is: a narrow size range or narrow Gaussian shaped curve implies a well-sorted sample, whereas a larger size range or ample Gaussian shaped curve implies a poorly sorted sample (i.e., a wide range of particle sizes). Moreover, the more asymmetric the curve is within a single distribution, or if the latter presents several frequency peaks (as seen in Figure 4), the greater modality of the sample: polymodality is shown by the greater frequency of distinct and different grain size range peaks. These different frequency groups are called populations and imply an ample modality of grain size fractions within the same sample, and vice versa.

Particle size distributions are based upon statistics, and description of the statistical parameters will usually depend on how the data are to be used. These calculated statistical parameters may give insight into various aspects of the environmental, depositional, and transport conditions the sediment grains endured, linking them to particular sedimentary systems. Three common parameters are the mean, the median, and the mode (Figure 4). The mean is the average size of the entire sample, as seen in Figure 4. The median is the diameter where 50 % of the particles are below or above that threshold. It is by far the easiest measure to determine but the least useful as it does not reflect the extremes of the curve (Folk, 1980). The mode is the particle size with the highest frequency, as seen in Figure 4, but it is not a good proxy of the overall sediment mixture (Folk, 1980). The only instance where all of these three parameters coincide is when the frequency distribution curve is a perfectly symmetrical Gaussian curve.

Other important statistical parameters obtained from the analysis of the distribution of particles – which can help elucidate how uniform, symmetrical, or well sorted the sediment sample is – are the standard deviation, skewness, and kurtosis (Folk, 1980). The standard deviation is a precise measure of the scatter of grain size values from the mean, corresponding then to a measure of spread or sorting of the sample. In combination with the mean, the standard deviation is the most useful and widely applied value in granulometric statistics. Three limits are useful when computing standard deviations within a single sample: 1 standard deviation ($\pm\sigma$) from the mean implies that 68 % of the grain size values fall within this limit;



Grain Size Analysis, Figure 4 Graphical representations of a grain size distribution: relative frequency distribution curve of a sediment sample, illustrating the statistical concepts of Median, Mode and Mean. Three different grain size “populations” can be depicted for this particular multimodal sample.

2 standard deviations ($\pm 2\sigma$) corresponds to 95 % of the particles; and 3 standard deviations ($\pm 3\sigma$) to 99 % (Folk, 1980).

The skewness is used to establish the normality or symmetry of the distribution, hence to quantify the degree of dispersion within a sample, rather than only visualizing it on a frequency histogram. The closer the skewness value is to zero, the more symmetrical (i.e., normal or unimodal) the distribution is. Asymmetrical and multimodal sediment mixtures exhibit high values of skewness, to maxima of +1.00 and −1.00. The positive and negative sign of the skewness value indicates whether the asymmetrical tail extends to the left or right of the curve as follows (Folk, 1980). Distribution curves highly skewed to low grain size values show a negative value and are diagnostic of environments with higher concentrations of silts and clays. The opposite are environments with higher concentrations of coarser materials which show curves skewed to higher grain sizes, hence positive values. Extremely turbid systems such as grain or turbidity flows are diagnostic of negatively skewed distributions. Tsunami, colluvial, debris flows, and torrential river deposits are diagnostic of positively skewed and multimodal distributions.

The kurtosis is also a quantitative measure to describe the degree of Gaussian normality of the grain size distribution, but in terms of how acute or flat the curve is. This is a sorting relation between the end members of the curve and its center (Folk, 1980). If the central portion of the curve is peaked, hence better sorted than its tails, the distribution curve is said to be leptokurtic with values >1.00. The opposite, a flat-peaked curve with a large spread of grain size in the center, is called platykurtic, with values <1.00. Normal probability curves have a kurtosis of 1.0 (Folk, 1980). Both kurtosis and skewness values are ratios of dispersion; thus, they are dimensionless and do not have units.

Summary

Grain size analysis is a fundamental tool for classifying unconsolidated materials and sediments, sedimentary rocks, and sedimentary environments. Quantitative analysis of the percentages of different particulate sizes yields one of the most fundamental physical properties of clastic sediments and sedimentary rocks. Grade scales, such as the geometric Udden-Wentworth or the logarithmic Krumbein Ø scales, which correspond to grain size intervals with a regular relationship to one another, were created to maintain a standardized statistical estimate of the measurement of the size of a particle, because grain size is considered a continuous variable. The almost exclusive purpose behind sizing grains is to obtain a frequency distribution of particle sizes.

A variety of principles and specific methodologies can be applied to differentiate and characterize the particle

sizes of unconsolidated materials and sediments or sedimentary rocks. The traditional analytical principles behind granulometry (counting, sieving, and settling) are still frequently used today, and in some instances, they cannot be superseded by modern techniques because certain particle ranges lie beyond the measureable limits of sensitive minuscule sensors. For this reason, when dealing with particle size analyses, it is also important to consider the particle size range of the material to be analyzed, how narrow or wide this might be, in order to select the most appropriate measurement method(s). Gravels and boulders are mostly counted manually. Pebble sizes can be determined by sieving. Sands, silts, and clays can be measured either by sieving (wet and dry conditions) or settling (hydrometer, pipette). However, automated modern techniques such as laser diffraction or dynamic light scattering can make the measurement process much faster and accurate than traditional techniques, and a greater number of samples can be analyzed at a time.

Selection of the particle size technique to use is dependent not only on the precision and accuracy required for each sample measurement, but also the skills of the operator and the time that can be spent per measurement. Another important factor to consider is the cost of the equipment and any consumables associated with that particular technique. The choice of method is basically dictated by the objective of the study and the degree of consolidation of the material. This is the reason why it is imperative to have an understanding of the complexity of the environmental system and/or archaeological site targeted for study, as well as the natural processes that may have affected the locale, both in past and present times, in order to have a better analytical appraisal of the environmental conditions and contributions of events to the resulting stratigraphical signatures.

Bibliography

Bruins, H. J., MacGillivray, J. A., Synolakis, C. E., Benjamini, C., Keller, J., Kisch, H. J., Klügel, A., van der Plicht, J., and Klügel, A., 2008. Geoarchaeological tsunami deposits at Palaikastro (Crete) and the Late Minoan IA eruption of Santorini. *Journal of Archaeological Science*, **35**(1), 191–212.

Folk, R. L., 1980. *Petrology of Sedimentary Rocks*. Austin: Hemphill Publishing.

Friedman, G. M., and Sanders, J. E., 1978. *Principles of Sedimentology*. New York: Wiley.

Jennings, B. R., and Parslow, K., 1988. Particle size measurement: the equivalent spherical diameter. *Proceedings of the Royal Society of London Series A*, **419**(1856), 137–149.

Krumbein, W. C., and Sloss, L. L., 1963. *Stratigraphy and Sedimentation*, 2nd edn. San Francisco: W. H. Freeman.

McManus, J., 1988. Grain size determination and interpretation. In Tucker, M. E. (ed.), *Techniques in Sedimentology*. Oxford: Blackwell Scientific, pp. 63–85.

Morhange, C., Salamon, A., Bony, G., Flaux, C., Galili, E., Goiran, J.-P., and Zviely, D., 2014. Geoarchaeology of tsunamis and the revival of neo-catastrophism in the Eastern Mediterranean. In Nigro, L. (ed.), *Overcoming Catastrophes: Essays on Disastrous Agents Characterization and Resilience Strategies in Pre-Classical Southern Levant*. Rome: La Sapienza Expedition to Palestine and Jordan. Rome «La Sapienza» Studies on the Archaeology of Palestine and Transjordan (ROSAPAT), Vol. 11, pp. 31–51.

Mostafa, M. H., Grimal, N.-C., and Nakashima, D. (eds.), 2000. *Underwater Archaeology and Coastal Management: Focus on Alexandria*. Coastal Management Sourcebooks 2. Paris: UNESCO.

Reinhardt, E. G., Goodman, B. N., Boyce, J. I., López, G. I., van Hengstum, P., Rink, W. J., Mart, Y., and Raban, A., 2006. The tsunami of 13 December A.D. 115 and the destruction of Herod the Great's harbor at Caesarea Maritima, Israel. *Geology*, **34**(12), 1061–1064.

Shepard, F. P., 1954. Nomenclature based on sand-silt-clay ratios. *Journal of Sedimentary Petrology*, **24**(3), 151–158.

Stanley-Wood, N., and Lines, R. W., 1992. *Particle Size Analysis*. Cambridge: Royal Society of Chemistry. Royal Society of Chemistry, Special Publication, 102.

Syvitski, J. P. M., 2007. *Principles, Methods and Application of Particle Size Analysis*. Cambridge: Cambridge University Press.

Udden, J. A., 1914. Mechanical composition of clastic sediments. *Bulletin of the Geological Society of America*, **25**(1), 655–744.

Wentworth, C. K., 1922. A scale of grade and class terms of clastic sediments. *Journal of Geology*, **30**(5), 377–392.

Cross-references

Alluvial Settings
Archaeological Stratigraphy
Coastal Settings
Colluvial Settings
Eolian Settings: Loess
Eolian Settings: Sand
Mass Movement
Optically Stimulated Luminescence (OSL) Dating
Paleoenvironmental Reconstruction
Scanning Electron Microscopy (SEM)
Sedimentology
Site Formation Processes
Soils
Tsunamis

GREAT PLAINS GEOARCHAEOLOGY

Vance T. Holliday[1] and Rolfe D. Mandel[2]
[1]Anthropology and Departments Geosciences, University of Arizona, Tucson, AZ, USA
[2]Department of Anthropology, University of Kansas, Lawrence, KS, USA

Introduction

The Great Plains area of North America has been the setting for pioneering geoarchaeological research in the Western Hemisphere. Many archaeological records in the region are in thick, stratified deposits, long recognized by archaeologists and geologists alike as important for understanding cultural chronology and Late Pleistocene and Holocene environmental change. In particular, understanding the Late Pleistocene peopling of the Americas has its origins in archaeological research on the Great Plains (Mandel, 2000). The list of geoscientists who have worked on archaeological projects in the Plains includes some of the most prominent figures to shape the discipline of geoarchaeology; among them have been Kirk Bryan, Ernst Antevs, Claude Albritton, Jr., E. H. Sellards, C. Bertrand Schultz, and C. Vance Haynes, Jr.

There are several historical reasons for the long record of geoarchaeological research in the Great Plains. Immediately following the excavations at the Folsom site in the Southern Plains, where from 1926 to 1928 the human association with extinct fauna was firmly established, archaeologists were attracted to the region because it was an area that repeatedly provided sites that contained human artifacts associated with Pleistocene fauna (Holliday, 2001). Because radiocarbon dating was not readily available until the 1950s, geologists and paleontologists were called upon to provide age estimates of those sites. Also, as outlined below, the Great Plains harbors many archaeological sites with cultural materials that are buried in thick, stratified deposits, especially in stream valleys. The Plains probably has a higher concentration of such sites than any other region of North America. On the Southern High Plains, many of the Paleoindian sites have thick, well-stratified deposits that provide evidence of depositional environments very different from those found in the region today, including meandering streams and perennial freshwater lakes, instead of dry valleys (draws) or dry lake basins (playas). During the early 1900s, these striking contrasts captured the attention of archaeologists and geoscientists alike (Holliday, 2001).

Another significant aspect of the long history of geoarchaeology on the Great Plains is the background and orientation of the archaeologists themselves. Some of the archaeologists, particularly in the early decades of Great Plains archaeology, were also trained as geologists and vertebrate paleontologists. In addition, many of the geologists and paleontologists working in the region had an interest in archaeology.

The evolution of geoarchaeology in the Great Plains was also influenced by the construction of dams during the 1920s and 1930s, especially in South Dakota. Those construction projects gave rise to campaigns of salvage archaeology, and geoscientists were sometimes called upon to place archaeological sites into geologic contexts. More consistent integration of geology with archaeology began with the development of interdisciplinary archaeological research in the 1950s and 1960s, followed by the rise of interdisciplinary cultural resource management in the 1970s.

Setting

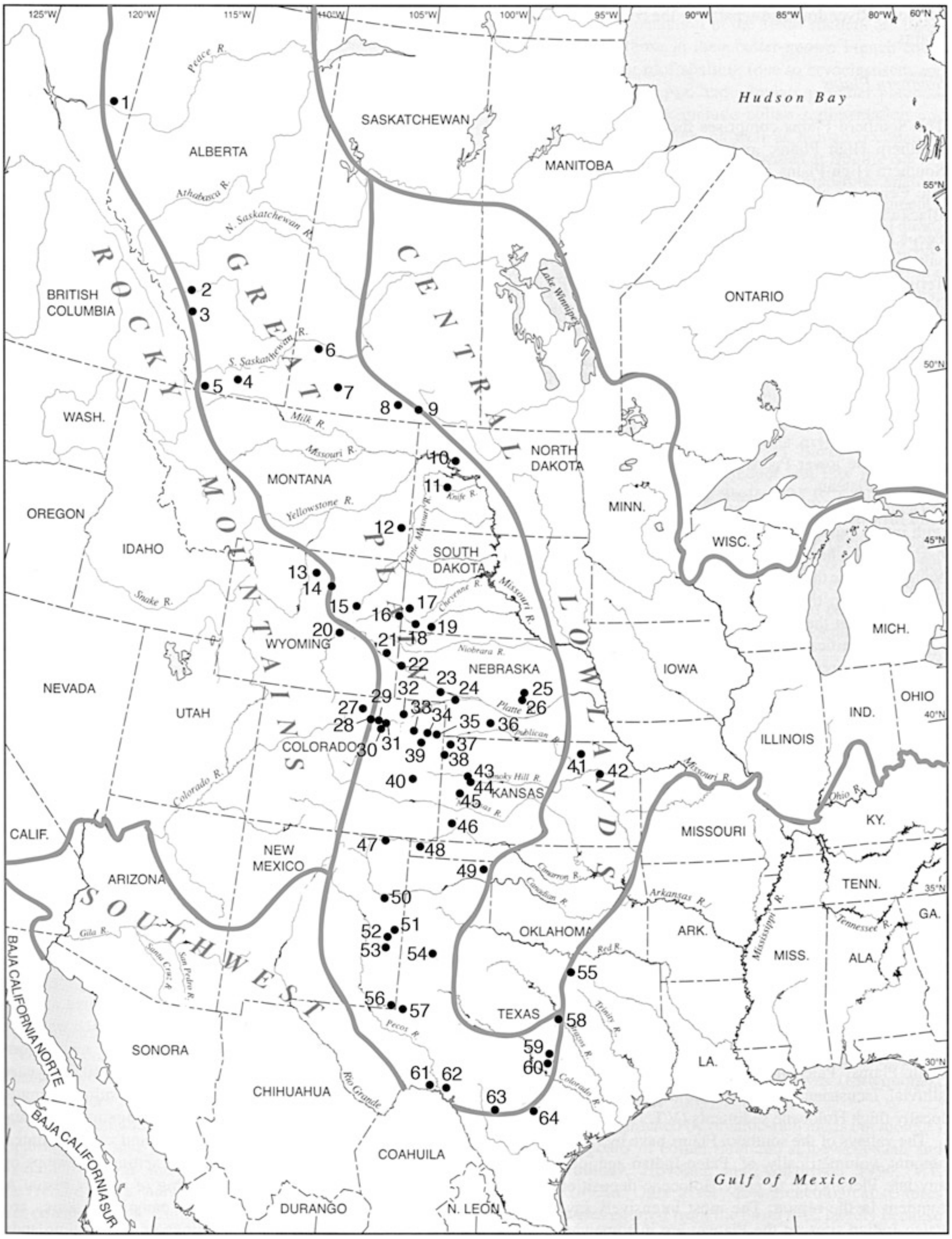
The Great Plains region encompasses an area of approximately 2,900,000 km^2 – roughly equivalent to one-third of the land area of the United States – making it one of the largest physiographic provinces in North America (Figure 1) (Wishart, 2011). According to Fenneman (1931), the Great Plains lies between the Rocky Mountains to the west, the Central Lowlands to the east, the Gulf Coastal Plain to the south, and the Canadian boreal forest to the north. This region can be divided into a dozen or so physiographic subprovinces or sections. There are few agreed-upon generalized groupings of these sections. For this discussion (following Holliday et al., 2002), the region is divided into the Southern, Central, and Northern Great Plains. Important subdivisions include the Alberta Plains and Missouri Plateau (Northern Great Plains), the Northern High Plains and Colorado Piedmont (Central Great Plains), and the Southern High Plains and Edwards Plateau (Southern Great Plains). We also include the Rolling Plains of Texas and Oklahoma and the western Central Lowlands in our discussion.

The Great Plains is stereotypically depicted as dry, monotonously flat grassland. However, the region contains woodlands, especially along streams, as well as diverse landscapes and many prominent landforms. The Raton Section of New Mexico, the Black Hills of South Dakota, and the Bear Paw, Big Snowy, and Judith Mountains of Montana, for example, rise 450–1,200 m above the surrounding plains. Low rolling hills, such as those of the Flint Hills and Smoky Hills in Eastern Kansas and the Rolling Plains of North Central Texas and South Central Oklahoma, also are common, as are deep valleys and canyons, such as the Canadian Breaks and Palo Duro Canyon in the Texas Panhandle and Ladder Creek valley in Western Kansas.

Several factors play a role in preserving archaeological sites and in forming stratified archaeological sequences on the Great Plains. Depositional environments – alluvial, lacustrine/palustrine, and eolian – since about 14,000 years ago (all dates are in uncalibrated radiocarbon years before present) generally have been aggradational. In particular, the valleys have been the setting of many meters of infilling, largely through floodplain aggradation, and localized lacustrine deposition. There are also extensive areas where eolian sand and silt aggraded during the Holocene. Thousands of small lake basins also dot portions of the Great Plains and most have slowly filled with sediment since the Last Glacial Maximum (LGM) about 20,000 years ago. A few rock-shelters occur in the region and have stratified archaeological records, but such sites are mostly limited to the Edwards Plateau, which consists of karstic limestone, and areas of the High Plains where differential erosion has left the thick, resistant caliche "caprock" (petrocalcic horizon) of the Ogallala Formation as an overhang.

Holocene archaeological stratigraphy

The long stratified archaeological records at many sites on the Great Plains have been key components in establishing regional cultural chronologies, typically in a dated context. Those stratigraphic records have also provided paleoenvironmental data tied to numerical chronologies. The stream valleys of the Edwards Plateau in Central Texas, particularly along the southern and eastern margins (also the southern and southeastern margin of the Great Plains), have provided rich sequences of artifacts spanning



Great Plains Geoarchaeology, Figure 1 Map of the mid-continent region of North America with physiographic provinces and locations of sites discussed in the text. (1) Charlie Lake Cave; (2) James Pass (EkPu8); (3) Vermilion Lake and Sibbald Creek; (4) Fletcher; (5) Wally's Beach; (6) Heron Eden; (7) Niska; (8) Dunn; (9) McLeod; (10) Beacon Island; (11) Knife River Flint Quarries; (12) Mill Iron (25CT30); (13) Medicine Lodge; (14) Sister's Hill; (15) Carter/Kerr-McGee; (16) Agate Basin; (17) Jim Pitts; (18) Ray Long; (19) Lange-Ferguson; (20) Casper; (21) Hell Gap; (22) Scottsbluff; (23) Clary Ranch; (24) 25KH67; (25) McKenzie; (26) Truman and Stark; (27) Lindenmeier; (28) Dent; (29) Klein and Frazier; (30) Jurgens; (31) Powars; (32) Fowler-Parrish; (33) Claypool; (34) Wray Dunes; (35) Jones-Miller; (36) Medicine Creek sites; (37) Powell; (38) Kanorado sites; (39) Dutton; (40) Olsen-Chubbock; (41) Coffey; (42) Claussen; (43) 12 Mile Creek; (44) Norton; (45) Simshauser; (46) Winger; (47) Folsom; (48) Nall; (49) Lipscomb; (50) San Jon; (51) Clovis/Blackwater Draw Location; (52) Elida; (53) Milnesand and Ted Williamson; (54) Lubbock Lake; (55) Aubrey; (56) Winkler-1; (57) Shifting Sands; (58) Horn Shelter #1 and #2; (59) Gault; (60) Wilson-Leonard; (61) Bonfire Shelter; (62) Baker Cave; (63) Kincaid Shelter; (64) Richard Beene.

Great Plains Geoarchaeology, Table 1 Selected Paleoindian sites in valleys and alluvial settings of the Southern Great Plains

Site	Setting	Geoarchaeology	References
Edwards Plateau			
Gault (Texas)	Upper Buttermilk Creek, Brazos River tributary	Multiple Clovis and Late Paleoindian occupations in thick (>1 m) alluvium near spring head	Collins and Brown, 2000
Wilson-Leonard (Texas)	Upper Brushy Creek, Brazos River tributary	Clovis, Folsom, Golondrina, Barber, St. Mary's Hall, San Patrice, and Angostura occupations in thick (>1 m) alluvium and cumulic soils	Bousman, 1998; Collins, 1998a; Collins, 1998b; Bousman et al., 2002
Richard Beene (Texas)	Lower Medina River, on the boundary between the Edwards Plateau and inner Gulf Coastal Plain	Stratified Angostura occupations in a deeply buried cumulic soil, plus stratified Archaic and Late Prehistoric cultural deposits in buried soils above the Angostura components	Thoms and Mandel, 2007; Mandel et al., 2007
Southern High Plains			
Clovis (Blackwater Draw Loc 1) (New Mexico)	Blackwater Draw, Brazos River tributary	Clovis with mammoth in spring alluvium; Folsom with bison in lake beds; Late Paleoindian with bison in wet meadow	Haynes and Agogino, 1966; Haynes, 1975, 1995; Holliday, 1995, 1997a
Lubbock Lake (Texas)	Yellow House Draw, Brazos River tributary	Clovis age with Pleistocene fauna in stream alluvium; Folsom with bison in lake beds; Late Paleoindian with bison in marshy wetlands	Stafford, 1981, Johnson, 1987; Holliday, 1985, 1995, 1997a; Holliday and Allen, 1987

the Holocene. No one site spans the past 12,000 years, but a set of sites, including Wilson-Leonard, Richard Beene, Clovis, Lubbock Lake, Coffey, and Medicine Lodge, covers the complete archaeological sequence.

Radiocarbon dating of the archaeological record at the Wilson-Leonard site on the Edwards Plateau in Central Texas (Figure 1) resulted in a high-resolution cultural sequence and geochronology for Paleoindian and Early Archaic occupations. Of particular significance, the combined archaeological and geological research revealed Archaic-style (stemmed) artifacts and subsistence strategies (broad spectrum with increased focus on plant gathering and processing) at ca. 12,000–10,250 cal years BP, stratigraphically interfingered with more classic Paleoindian lanceolate artifact styles. This sequence provides a rare glimpse of the Paleoindian to Archaic transition in both artifact styles and subsistence practices.

The Richard Beene site (Table 1), located on the boundary between the Edwards Plateau and Inner Gulf Coastal Plain in South Central Texas (Figure 1), is a well-dated stratified locality with numerous discrete and substantial artifact and feature assemblages that span the Holocene (Thoms and Mandel, 2007). There are 20 stratigraphically distinct archaeological horizons that have yielded more than 80,000 artifacts, including flakes, tools, bones, mussel shells, and fire-cracked rocks, buried in 14 m of fine-grained, over-bank alluvium comprising a terrace fill. Nearly all of the cultural deposits are associated with buried soils that formed during relatively brief episodes of landscape stability (Mandel et al., 2007). The site's archaeological record provides a uniquely long-term perspective on regional paleoecology and riverine usage in an ecotone between North America's western grasslands and eastern woodlands. Throughout its 10,000-year history of intermittent habitation, hunter-gatherer families occupied the site, camping along the Medina River; hunting deer, rabbits, and other game in wooded areas; gathering wild roots; and fishing and collecting river mussels to supplement their diet. Climatic conditions fluctuated through the period of occupation but usually did not vary much from modern conditions (Thoms and Mandel, 2007).

The Clovis and Lubbock Lake sites (Table 1), both on the Southern High Plains (Figure 1), are best known for their stratified Paleoindian archaeological records (discussed below), but they also contain younger cultural deposits in valley fills. The Paleoindian to Archaic transition is not well recorded because of low sedimentation rates, but occurred ~8,500–8,000 years BP. This transition was roughly coincident with Early Holocene aridity that triggered widespread eolian sedimentation in valleys ~6,000–4,500 year BP (Middle Holocene/Middle Archaic). The Archaic to Late Prehistoric transition is also difficult to identify in the archaeological record because of regional landscape stability and very limited sedimentation but was probably ~2,000 year BP. Localized landscape instability and cyclic episodes of slope wash deposition and stability in the Late Holocene at Lubbock Lake provide a high-resolution archaeological record of the Late Prehistoric to Protohistoric transition, as well as the Protohistoric to Historic transition, including differentiation of Native American Historic and Euro-American Historic occupations.

At the Coffey site (Table 2) in the Flint Hills of Northeastern Kansas (Central Plains) (Figure 1), stratified Middle Paleoindian (Folsom and Midland) through Late Woodland cultural deposits occur in valley fill beneath the T-1 terrace of the Big Blue River, and Early Paleoindian (Clovis) projectile points have been recorded

Great Plains Geoarchaeology, Table 2 Selected Paleoindian sites in valley and alluvial settings on the Central Great Plains

Site	Setting	Geoarchaeology	References
Northern and Central High Plains			
Hell Gap (Wyoming)	Small valley with low-order tributary to North Platte River	Goshen, Folsom, Midland, Agate Basin, Hell Gap, Alberta, Cody, and Frederick occupations (locally redeposited) in stratified eolian and alluvial silts	Frison, 1998; Kornfeld, 2005; Larson et al., 2009
Medicine Creek sites – Lime Creek, Red Smoke, Allen (Nebraska)	Medicine Creek, tributary to Republican River	Stratified Cody, Frederick, and other Late Paleoindian occupations in thin buried soils near base of thick, silty alluvium	Davis, 1953, 1962; Roper, 2002; May, 2002
Jones-Miller (Colorado)	Terrace of Arikaree River	Hell Gap bison bone bed in and along swale on terrace	Albanese, 1977; Stanford, 1978, 1984
Olsen-Chubbuck (Colorado)	Arroyo	Firstview/Cody bison kill deeply buried under arroyo fill	Wheat, 1972; Holliday et al., 1999
Scottsbluff (Nebraska)	Terrace of Spring Creek, tributary to the North Platte River (near base of Signal Butte)	Scottsbluff-type (Cody) bison kill on terrace gravel, buried by sand and silt	Barbour and Schultz, 1932, 1936; Schultz and Eiseley, 1935; Knudson, 2013
Truman (Nebraska)	A terrace remnant at the mouth of Kilgore Creek where it joins the South Loup River	Three stratified Paleoindian cultural components, including one identified as early Cody complex (Alberta), in terrace fill	May and Holen, 2014
Stark (Nebraska)	Gully along the margin of an unnamed, flat-bottomed, first-order tributary to the lower South Loup River	Cody complex (Scottsbluff) component buried in gully fill	May and Holen, 2014
McKenzie (Nebraska)	Alluvial fan in the Middle Loup River valley	At least seven stratified components ranging from Early Paleoindian to Late Prehistoric in fan deposits	May and Holen, 2014
Clary Ranch (Nebraska)	Terrace of Ash Hollow Creek, tributary to North Platte River	Allen/Frederick bison bone bed in alluvium	Myers et al., 1981; Hill et al., 2002a; Hill et al., 2002b
Norton (Kansas)	Arroyo along Ladder Creek, a tributary to the Smoky Hill River	Allen/Frederick bison bone bed deeply buried in arroyo fill	Hofman et al., 1995
Kanorado (Kansas)	Middle Beaver Creek, a tributary to the Republican River	Stratified Clovis *Camelops* bone bed and pre-Clovis mammoth and *Camelops* in alluvium	Mandel et al., 2004
Lipscomb (Texas)	Arroyo along Sand Creek, a tributary to the North Canadian River	Folsom bison bone bed along arroyo margin	Barbour and Schultz, 1941; Hofman, 1995; Holliday, 1997a
Central High Plains – Central Lowlands Border			
Coffey (Kansas)	Terrace of the Big Blue River	Stratified Folsom, Midland and Late Paleoindian cultural deposits in an alluvial soil	Mandel et al., 2010; Ray and Mandel, 2014
Claussen (Kansas)	Terrace of Mill Creek	Stratified Dalton cultural deposits in a deeply buried alluvial soil	Mandel et al., 2006
Colorado Piedmont			
Lindenmeier (Colorado)	Small valley with arroyo tributary of Cache La Poudre River	Multiple Folsom camps and bone bed in slowly aggrading, stratified soils	Bryan and Ray, 1940; Haynes and Agogino, 1960; Wilmsen and Roberts, 1978
Dent (Colorado)	Terrace of South Platte River	Clovis mammoth bone bed in alluvium; redeposited	Haynes et al., 1998; Brunswig, 2007
Klein (Colorado)	Terrace of South Platte River	Clovis artifacts, mammoth and horse in gravely alluvium	Zier et al., 1993
Jurgens (Colorado)	Terrace of South Platte River	Cody bone bed in swale; camp on ridge	Wheat, 1979; Holliday, 1987; McFaul et al., 1994
Frazier (Colorado)	Terrace of South Platte River	Agate Basin bone bed in swale	Malde, 1984; Holliday, 1987; McFaul et al., 1994
Raton section			
Folsom (New Mexico)	Arroyo tributary to Dry Cimarron River	Folsom-type collection and bone bed in fine-grained (eolian) arroyo fill	Meltzer et al., 2002; Meltzer, 2006

on the T-2 terrace (Schmits, 1980; Mandel et al., 2010; Mandel, 2014). Hence, Coffey harbors one of the most complete records of human occupation in the Great Plains. The site is best known for yielding significant information about Middle Archaic occupation of the Central Plains from ~5,500 to 5,000 year BP, one of the least documented periods in Plains prehistory. The archaeological record at locality 1 consisted of a rich array of features,

Great Plains Geoarchaeology, Table 3 Selected Paleoindian sites on the Missouri Plateau, Northern Great Plains

Site	Setting	Geoarchaeology	References
Agate Basin[a] (Wyoming)	Arroyo tributary to Moss Agate Creek (Cheyenne River)	Clovis, Folsom, Agate Basin, and Hell Gap occupations in stratified arroyo fill and associated buried soils	Albanese, 1982; Frison and Stanford, 1982; Reider, 1982
Carter/Kerr-McGee (Wyoming)	Arroyo tributary to Powder River	Clovis, Folsom, Agate Basin-Hell Gap, and Alberta-Cody occupations in stratified arroyo fill and associated in poorly drained buried soils	Frison, 1984; Reider, 1980, 1990
Sister's Hill (Wyoming)	Arroyo tributary to Powder River	Hell Gap camp in poorly drained soil within stratified alluvium	Agogino and Galloway, 1965; Haynes and Grey, 1965; Reider, 1983
Casper (Wyoming)	Dune on terrace of North Platte River	Hell Gap bison kill in parabolic sand dune	Albanese, 1974; Frison, 1974
Jim Pitts (South Dakota)	Black Hills foothills	Stratified Folsom, Goshen, Agate Basin, Cody, and Alberta camp sites in aggrading soil (Leonard paleosol)	Sellet, 2001; Sellet et al., 2009
Mill Iron (Montana)	Butte above tributary to Box Elder Creek	Goshen bison kill on alluvial and colluvial surface in paleo-swale draining to creek	Albanese, 1996; Frison, 1996; Reider, 1996
Knife River Flint Quarries – Alkali Creek, Bobtail Wolf, Big Black, Benz (North Dakota)	Low terrace along Spring Creek	Goshen, Folsom, and Hell Gap artifacts in alluvium; Folsom, Cody, and Alberta occupations in eolian sand and silt	Root et al., 1985; Artz, 1995; Metcalf and Ahler, 1995; Root, 2000; Williams, 2000
Medicine Lodge (Wyoming)	Alluvial terrace and colluvial apron along the Medicine Lodge Creek	Over 60 cultural levels spanning the past 10,000 years contained in an 8-m-thick alluvial-colluvial sequence adjacent to a rock-shelter	Frison, 1976

[a]Includes Sheaman and Brewster localities

faunal remains (especially bison), and artifacts contained within 12 stratified cultural horizons in unit III, a fine-grained alluvial fill that aggraded between ~6,000 and 5,000 year BP (Schmits, 1980; Mandel et al., 2010). Recent geoarchaeological investigations at Coffey recorded stratified Middle and Late Paleoindian cultural deposits in a paleosol developed at Late Wisconsinan alluvial fill (Ray and Mandel, 2014), adding to the significance of the site.

The Medicine Lodge site (Table 3), located on the edge of the Bighorn Basin in North Central Wyoming (Figure 1), consists of over 60 cultural levels spanning the past 10,000 years, making it the most complete record of human occupation in the northern Plains. The cultural deposits are contained in an 8-m-thick alluvial-colluvial sequence adjacent to a rock-shelter (Frison, 1976). Five distinct vegetation zones occur within a radius of 19 km around the site, which provided a rich resource base for the inhabitants of the site. Analyses of faunal remains, seeds, pollen, and charcoal from Medicine Lodge, as well as the site stratigraphy, yielded information used to reconstruct Holocene paleoenvironments in the Bighorn Basin (Frison, 1976).

Paleoindian geoarchaeology

Beginning in the nineteenth century, acrimonious debate often surrounded the subject of the timing of the earliest peopling of the Americas, and the disagreements lasted for decades. The basic arguments were over a short chronology (people had been in the Americas for only a few thousand years) versus a long chronology (ancestors of Native Americans arrived in the Late Pleistocene). In the late 1920s, the debate was finally settled with the discovery of the Folsom site in eastern New Mexico, on the Southwestern Great Plains. Basic stratigraphy and paleontology at Folsom showed that artifacts (projectile points for hunting) were in association with extinct Late Pleistocene bison. This discovery launched the subdiscipline of Paleoindian archaeology and the beginning of considerable geoarchaeological research with a focus on the earliest sites in the Americas. This entry will describe in some detail that focus on Paleoindian settlement in the Great Plains.

Since the initial Folsom discoveries, combined archaeological and geological investigations of Paleoindian sites continued throughout the Great Plains. Because sedimentation was relatively continuous and because of, for the most part, low energy in stream valleys and lake basins throughout much of Plains during the Late Pleistocene and Early Holocene (as described below), the region has the highest concentration of known, in situ, stratified archaeological sites for this period anywhere in the Americas (see Mandel, 2000).

Valleys and draws

Thick, continuous stratigraphic sequences of alluvium are a striking characteristic of the drainages of the Great

Great Plains Geoarchaeology, Figure 2 Excavations in bedded diatomite and overlying homogeneous muds at the Lubbock Lake site, Northwestern Texas. These lake and marsh beds formed on the floor of Yellow House Draw, a tributary of the Brazos River. The bedded diatomite (on which most of the crew stands) contains a Late Paleoindian bone bed of extinct bison (*Bison antiquus*) dating to ~11,500 cal years BP. The smaller excavated area low in the diatomite contains a Folsom-age *B. antiquus* bone bed dating to ~12,500 cal years BP. Homogeneous palustrine mud on top of the bedded diatomite is about 50 cm thick, exposed low along the back wall of the excavations. Note the lack of deformation of the beds despite the multiple bison-butchering activities (From Holliday, 1997a: Figure 3.28).

Plains. Stratified archaeological sequences are likewise ubiquitous. This situation is largely the result of deep incision between the LGM and Younger Dryas by most stream systems, followed by aggradation and episodic stability through most of the rest of the Late Quaternary. The Paleoindian archaeological sites therefore tend to be deeply buried. For example, at the Aubrey site on the Trinity River in Northeast Texas (Figure 1), Clovis cultural deposits lie beneath ~8 m of alluvium (Ferring, 2001). At the Claussen site on lower Mill Creek, a high-order stream in the Flint Hills of Northeast Kansas (Figure 1), multiple Dalton (Late Paleoindian) occupation zones occur ~9–10 m below the surface of an alluvial terrace (Mandel et al., 2006). Along the perennial streams of the Plains, many early sites are likely below the water table. As a result, most of the recorded Paleoindian sites are in draws (dry valleys) and arroyos (dry washes) in low-order tributaries.

The most intensively investigated, stratified Paleoindian sites on the Edwards Plateau are in somewhat similar settings: low-order tributaries incised into the limestone bedrock and in proximity to springs (Table 1). Besides their setting, both Wilson-Leonard and Gault (Figure 1) exhibit remarkably similar stratigraphic sequences: (1) multiple Paleoindian occupations in thick (>1 m), well-stratified sediments (Table 1); (2) a fining-upward sequence of alluvium during the Early Paleoindian period from ~11,500 to 10,000 years BP; and (3) stability and soil formation beginning ~10,000 years BP and lasting ~500–1,000 radiocarbon years, then colluvial and alluvial deposition coincident with Late Paleoindian and Early Archaic occupations.

The draws of the Southern High Plains are now dry tributaries of the Red, Brazos, and Colorado rivers (Haynes, 1975, 1995; Stafford, 1981; Holliday, 1995, 1997a). Clovis occupations, characterized by mammoth kills and megafauna processing, are associated with active alluvial settings such as point bars and spring-fed drainageways (Table 1). Flowing water gave way to standing water in ponds and marshes during the Folsom occupation. Bone beds of extinct *Bison* with Folsom artifacts were recovered from microstratified diatomite beds and muds (Figure 2). These deposits formed in lakes that were scattered along the floors of several draws. By 10,000 year BP, the draws were characterized by deposition of muds, carbonates, and localized eolian sand. Late Paleoindian occupations characterized by Plainview, Firstview/Cody, and other unfluted lanceolate styles were found in these settings in camps or in bone beds from kills or processing of extinct *Bison*. A few Folsom and Late Paleoindian camping features are also recorded from valley-margin settings or from the uplands immediately adjacent to the draws (Holliday, 1997a).

Draws on the Northern High Plains also have yielded stratified Paleoindian cultural deposits (Mandel, 2006). Specifically, the Kanorado locality in Northwest Kansas (Figure 1) is on the valley floor of Middle Beaver Creek, a draw that today carries water only immediately after heavy rainfalls. A cluster of three sites at Kanorado has deeply buried Early Paleoindian and Folsom cultural deposits with disarticulated remains of mammoth and extinct bison, respectively (Mandel et al., 2004, 2009). During the period of Early Paleoindian occupation (11,000 years BP), the site was characterized by standing water in spring-fed ponds surrounded by a savanna with coniferous trees and C_3 grasses (Cordova et al., 2011). The ponds were beginning to dry up during the Folsom occupation (~10,350 years BP), and the number of drought-adapted C_4 Chloridoideae grasses increased at the expense of the C_3 grasses and woody plants. Other stratified Paleoindian occupations associated with draws on the Northern High Plains include the Powell site (Mandel et al., 2004) and Simshauser site (Mandel and Hofman, 2006) in Northwestern and Southwestern Kansas, respectively, and the Clary Ranch locality in Southwestern Nebraska (May et al., 2008) (Figure 1).

Several better-known Paleoindian sites on the Great Plains are associated with the upper South Platte River and its tributaries in the Colorado Piedmont, the broad topographic basin between the High Plains and Rocky Mountains created by the upper South Platte and Arkansas rivers (Figure 1; Table 2). The sites tend to be near the top of Late Pleistocene alluvium (Dent and Klein Clovis sites, Figure 1; Table 2) or on top of the associated terrace (mapped as the Broadway terrace near Denver and the Kersey terrace in the Greeley area) (Powars Folsom site; Jurgens and Frazier Late Paleoindian sites, Figure 1, Table 2). Clovis material appears to be in the upper alluvium, while Folsom and other post-Clovis occupations are on top of the terraces, buried by thin layers of mud (Frazier and Jurgens sites) or by eolian sand (Powars Folsom site). The data suggest that the upper South Platte was in the early stages of entrenchment from Clovis through Late Paleoindian times.

The famous Lindenmeier site (Figure 1; Table 2) is in an unusual valley setting: a low-order tributary of the Cache La Poudre River, which joins the South Platte (Figure 1). Scouring of the small valley preceded the Folsom occupation; hence, Clovis-age erosion far up a - low-order tributary of the South Platte was coincident with the final stages of mainstream alluviation. Downcutting was followed by slow aggradation and pedogenesis during the Folsom occupation.

Geoarchaeological data for Paleoindian sites along other mainstreams and tributaries on the Central Great Plains, particularly the High Plains, provide a sharp contrast with the record on the upper South Platte. Medicine Creek, Nebraska, a tributary of the Republican River (which flows into the South Platte), yielded three prominent Late Paleoindian sites (Allen, Lime Creek, and Red Smoke; Figure 1, Table 2), all deeply buried beneath floodplain silt that was likely derived from loess on the uplands (Figure 3). Likewise, Late Paleoindian sites along the North Platte (Scottsbluff), Loup (Truman, Stark, and McKenzie), and Smoky Hill rivers (12 Mile Creek and Norton) are deeply buried in alluvium (Figure 1, Table 2). Thus, while the mainstream upper South Platte was quasi-stable or downcutting in Paleoindian times, lower-order tributaries and adjacent mainstreams had already undergone deep entrenchment and were aggrading during the Paleoindian occupation of the region.

Geoarchaeological data are sparse for the Missouri Plateau, particularly from Paleoindian sites, given its size in comparison to the Central and Southern Great Plains. This is likely due to extensive alluvial erosion in this headwater setting of the Missouri River system. The principal exceptions are in headwater areas of the major drainages in Wyoming and Montana.

Most known and investigated Paleoindian sites in the Missouri Plateau were exposed along arroyos in low-order tributaries, particularly in the headwater areas. These exposures yielded a number of key Paleoindian sites, including Carter/Kerr-McGee, Sister's Hill, Agate Basin, and Lange-Ferguson (see Albanese, 2000) (Figure 1; Table 3). Most of these occupations are associated with buried soils exhibiting evidence of poor drainage, which suggests that local water tables were high at the time (e.g., Sister's Hill, Agate Basin, Carter/Kerr-McGee). But changes in soil morphology also indicate that the wetlands dried through Paleoindian time.

Two of the few Paleoindian sites in mainstream settings of the Missouri Plateau provide unique insights into Paleoindian activities: Beacon Island and the Knife River Flint Quarries. Beacon Island is a multicomponent archaeological site in northwestern North Dakota that includes an Agate Basin (Paleoindian) component consisting of the butchered remains of at least 29 *Bison antiquus*, along with projectile point fragments and other artifacts (Mandel et al., 2014) (Figure 1). The bison bone bed is a product of a single kill at ca. 10,300 years BP, and it is buried in a shallow kettle basin (Figure 4). Based on phytolith and stable carbon isotope data, cool-season C_3 prairie species dominated the site at the time of the bison kill. Although the Agate Basin occupation coincided with the coolest and perhaps the wettest climatic episode during the past 12,000 years, it is likely that the people associated with the Agate Basin culture at Beacon Island did not experience environmental conditions dramatically different from the modern conditions at the site (Mandel et al., 2014).

The well-known Knife River Flint Quarries are found along the Knife River and its tributary Spring Creek (Figure 1). Knife River flint is a high-quality raw material for stone tool manufacture used throughout the human occupation of the Northern Great Plains and adjacent areas (Clayton et al., 1976; Ahler, 1986; Root, 2000). The flint occurs in Pleistocene alluvium and colluvium in both fill

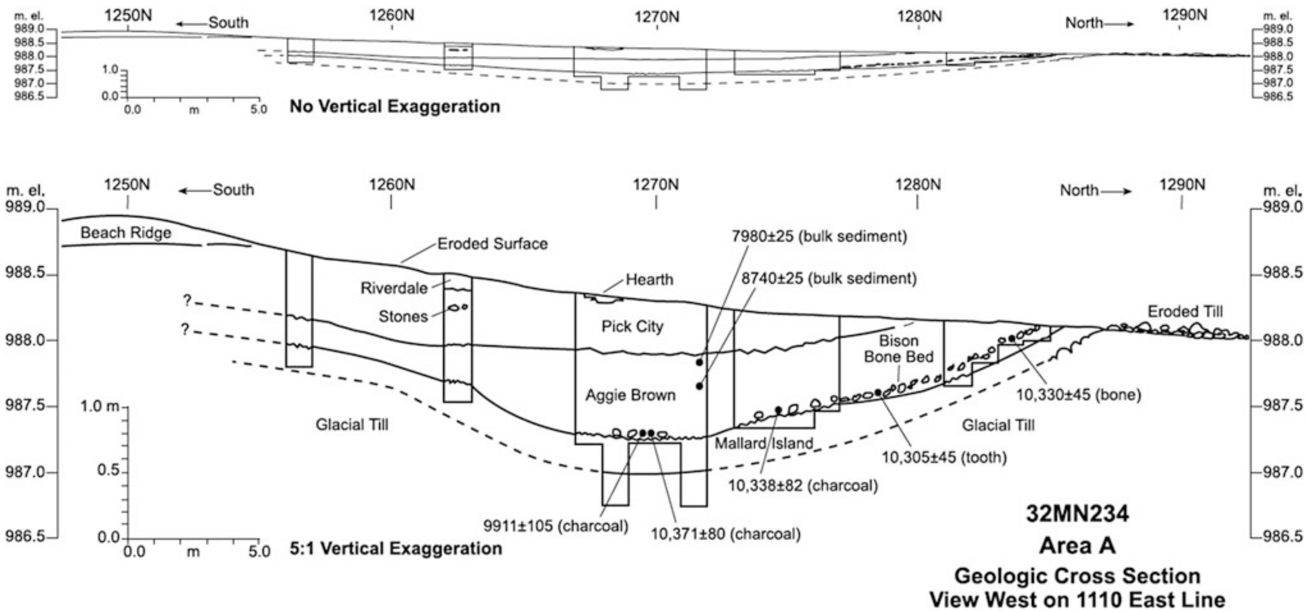
Great Plains Geoarchaeology, Figure 3 Photograph of the 1947 excavations at the Lime Creek site (25FT41) in Southwestern Nebraska. Late Paleoindian cultural deposits associated with a buried soil at the bottom of the exposure are mantled by 12 m of silty alluvium derived from Late Quaternary loess on the uplands (Photo courtesy of the University of Nebraska State Museum).

and strath terraces (Figure 5). In the reported sites (Table 3), the flint was at or just below the surface during the various Paleoindian occupations of the area (Artz, 1995; Van Nest, 1995; Root, 2000; William, 2000).

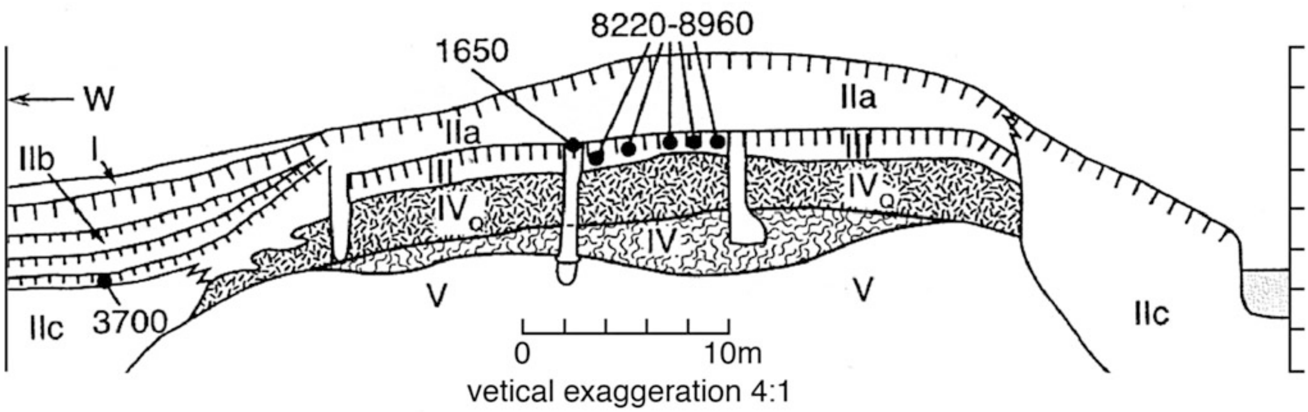
The Alberta Plains was deglaciated essentially coincident with the peopling of the New World as the Laurentide and Cordilleran ice sheets retreated at the end of the LGM and opened the gateway (the "ice-free corridor") between Beringia and the Americas. As the area was deglaciated, proglacial lakes probably covered the landscape. Drainage of the lakes likely resulted in deep incision of the meltwater channels, followed by rapid filling of these drainageways. These processes probably explain the relative absence or lack of visibility of early archaeological sites in the region. Most of the well-documented Paleoindian sites on the Alberta Plains for which geological data are available are in valleys in or near foothills of the Canadian Rockies. The early occupations at Vermilion Lakes (~10,800 year BP) and Charlie Lake Cave (~10,500 year BP) are associated with slope wash or debris-flow deposits owing to the footslope settings, but the ancient inhabitants may have been attracted by proglacial lakes once located in the valleys where the sites are situated (Figure 1; Table 4). There are indications of Clovis hunting at Wally's Beach. Butchered remains of extinct horse were found on alluvium and buried by eolian sand along the St. Mary River, just east of the foothills (Table 4) (Kooyman et al., 2006).

Lakes and playas

Lakes, dry lake basins, and playas (seasonally dry basins; "pans" in other regions) are locally common on the Great Plains, largely on the level and poorly drained High Plains and Alberta Plains. On the Southern High Plains, Paleoindian archaeology is common around basin margins (Hester, 1975; Litwinionek et al., 2003), but these relatively stable settings rarely produce buried archaeological features. The only in situ Paleoindian features known from playas are in the basin fills, but only three are known



Great Plains Geoarchaeology, Figure 4 Stratigraphic cross section of area A of the Beacon Island site. The beach ridge on the southern margin of the kettle basin is associated with modern Lake Sakakawea (From Mandel et al., 2014).



Great Plains Geoarchaeology, Figure 5 Stratigraphic cross section through the Alkali Creek site, one of the Knife River Flint Quarries, showing the relationship of the Paleoindian occupation surface to the Leonard Paleosol (unit III), the high-quality flint gravel (unit IV), and quarry spoil in the gravel (unit IV_Q). Units I–II are Holocene alluvium, and unit V is Pleistocene alluvium. Numbers are uncalibrated radiocarbon years before present (From Holliday and Mandel, 2006: Figure 3).

(Table 5), largely because exposures, natural or artificial, are rare.

Playa basins on the Northern High Plains have received significantly less attention stratigraphically, geoarchaeologically, and geomorphologically than their southern counterparts but have produced in situ Paleoindian finds (Table 6). For example, the Winger site, a Late Paleoindian bison kill located in southwestern Kansas (Figure 1), is on the edge of a playa basin (Mandel and Hofman, 2003). The bison bone bed is in a deeply buried soil developed in fine-grained basin fill overlain by Early Holocene alluvium (arroyo fill). Allen points and point fragments were recorded in the bone bed. Limited excavation revealed some fully articulated skeletons, and taphonomic observations suggest some of the bison collapsed while standing in a playa or pond margin setting. The remains of at least six bison are represented in the excavated sample, but many more animals are represented in the bone bed. A radiocarbon age of ~9,000 year BP was determined on bone collagen, which is consistent with the diagnostic artifacts found at Winger.

Great Plains Geoarchaeology, Table 4 Selected Paleoindian sites on the Alberta Plains, Northern Great Plains

Site	Setting	Geoarchaeology	References
Charlie Lake Cave (British Columbia)	Peace River	Multiple occupations 10,500 (including fluted style)– 9,500 ^{14}C years BP in slope wash below rock-shelter	Fladmark et al., 1988
Vermilion Lake (Alberta)	Mountain footslope, Bow River valley, Alberta Front Ranges	Multiple occupations 10,800–9,000 ^{14}C years BP (including stemmed lanceolates) in stratified debris-flow deposits and eolian silt and sand	Fedje, 1986; Fedje et al., 1995
Sibbald Creek (Alberta)	Outwash terrace, Alberta Front Ranges	Fluted and unfluted lanceolate styles in ~50-cm surface mantle of unstratified silty loam	Gryba, 1983
Fletcher (Alberta)	near Chin Coulee, on plains uplands	Cody artifacts with bison in pond muds or alluvium	Forbis, 1968; Vickers and Beaudoin, 1989
Niska (Saskatchewan)	Old Wives Lake plain	Cody (and older) artifacts in eolian sand sheet along meltwater channel	Meyer, 1985
Dunn (Saskatchewan)	Missouri Coteau, Ogema basin	Cody occupation in sand sheet along meltwater channel with wetland	Ebell, 1988; Meyer and Liboiron, 1990
McLeod (Saskatchewan)	Missouri Coteau, Long Creek drainage	Cody occupation in sand ridge along ephemeral wetland	Joyes, 2000
Heron Eden (Saskatchewan)	Glacial Lake Stewart Valley, near Great Sand Hills	Cody bone bed in eolian sand and silt with buried soil	Linnamae, 1998; Beaudoin and Lemmen, 2000
Wally's Beach (Alberta)	St. Mary River	Late Pleistocene fauna and Clovis points on an island ~11,300–11,000 ^{14}C years BP	Kooyman et al., 2001, 2006

Great Plains Geoarchaeology, Table 5 Selected Paleoindian sites in or around lake basins and in sand dunes on the Southern High Plains

Site	Setting	Geoarchaeology	References
Lake basins			
San Jon (New Mexico)	Eroded playa basin near northwest edge of S. High Plains	Firstview/Cody bone bed in playa mud	Roberts, 1942; Judson, 1953; Hill et al., 1995, Holliday, 1997a
Miami (Texas)	Small, filled playa basin near northeast edge of S. High Plains	Clovis with mammoth in playa mud	Sellards, 1938; Holliday et al., 1994
Ryan (Texas)	Small, filled playa basin	Cache of Plainview points (13) in playa mud	Hartwell, 1995; Holliday, 1997a
James Pass (Alberta)	Bedrock bench on the margins of a basin surrounded by mountains	Stratified Late Paleoindian and Early Archaic cultural deposits beneath the Mazama Ash	Ronaghan, 1993
Dunes			
Milnesand (New Mexico)[a]	Lea-Yoakum Dunes	Milnesand-type artifacts and bison bone bed in eolian sand	Sellards, 1955; Warnica and Williamson, 1968; Holliday, 1997a; Hill, 2002
Ted Williamson (New Mexico)[a]	Lea-Yoakum Dunes	Plainview artifacts and bison bone bed in eolian sand	Holliday, 1997a
Elida (New Mexico)	Lea-Yoakum Dunes	Folsom camp in eolian sand, adjacent to small playa basin	Warnica, 1961; J. Hester, 1962; Holliday, 1997a
Shifting Sands (Texas)	Andrews Dunes	Folsom/Midland camp and bison processing site in eolian sand	Amick and Rose, 1990; Hofman et al., 1990; Holliday, 1997a

[a]Milnesand and Ted Williamson sites are 550 m apart

Six of the seven reported Paleoindian sites in playa basins on the High Plains are essentially single component features (e.g., a bone bed from a kill or an artifact cache) located on the basin floors. The Nall site is unusual among Paleoindian sites in either playa or eolian sediments in that it lies along a playa margin, and it yielded a record of occupation throughout Paleoindian time (Table 6). This is probably because the occupation area was around or near likely springs or seeps (LaBelle et al., 2003).

Great Plains Geoarchaeology, Table 6 Selected Paleoindian sites in or around lake basins and in dune fields, Central and Northern Great Plains

Site	Setting	Geoarchaeology	References
Alberta Plains			
James Pass (Alberta)	Bedrock bench on the margins of a high-elevation basin	Late Paleoindian occupation beneath Mazama volcanic ash	Ronaghan, 1993
Northern High Plains			
Dutton (Colorado)	Playa	Clovis occupation in stratified playa fill	Stanford, 1979; Reider, 1990
Claypool (Colorado)	Playa in the Wray dune field	Cody occupation in stratified eolian sand; Clovis artifact in possible association with mammoth in lake marl	Dick and Mountain, 1960; Malde, 1960; Stanford and Albanese, 1975; Reider, 1990
Yuma and Washington counties (Colorado)[a]	Blowouts in the Wray dune field	Wide array of Paleoindian artifact styles; some apparently associated with lake, marsh, or spring deposits	Renaud, 1931, 1932 Gebhard, 1949; LaBelle, 2002
Nall (Oklahoma)[a]	Dunes along playa margin	Multiple Paleoindian occupations (Clovis, Folsom-Midland, Agate Basin, Cody/Firstview, but mostly Allen/Frederick, Plainview) in stratified eolian sediment and spring-fed marsh muds	Baker et al., 1957; LaBelle et al., 2003
Colorado Piedmont			
Powars (Colorado)[b]	Dune on terrace of S. Platte River	Folsom occupation in eolian sand	Roberts, 1937, 1940; Holliday, 1987
Fox (Colorado)[a]	Dune on terrace of S. Platte River	Clovis occupation in eolian sand	McFaul et al., 1994
Fowler-Parrish (Colorado)	Dune field (and playa)	Folsom bison kill in stratified eolian sand	Agogino and Parrish, 1971

[a]Large surface collections
[b]Also listed in alluvial table

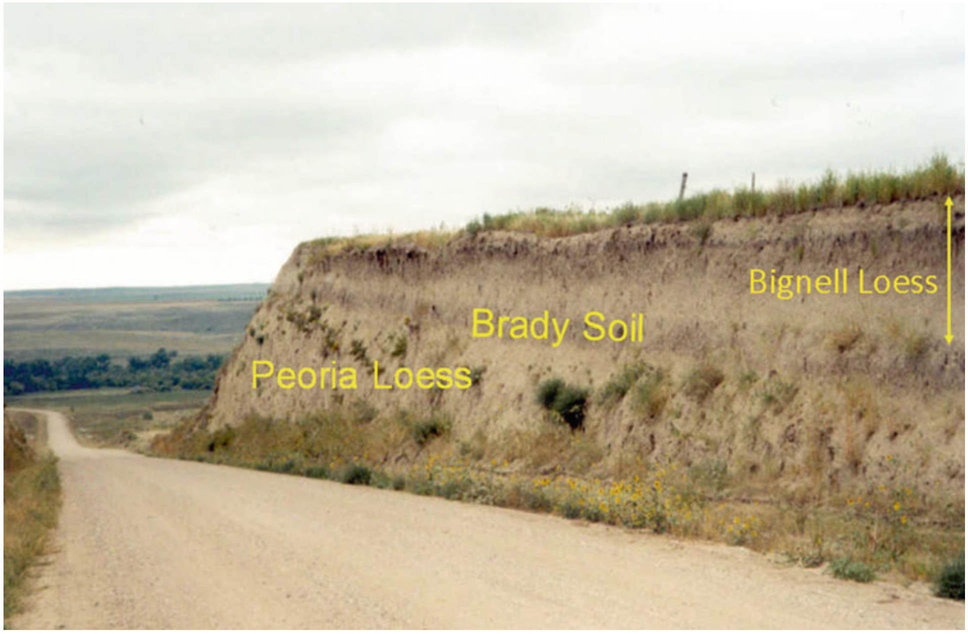
The few Paleoindian sites known and reported on the Alberta Plains away from the Rocky Mountain front tend to be associated with either lake or marsh sediments or nearby wetlands. Most fluted point sites are near extinct lakes (Gillespie, 2002, 120–123). Proglacial lakes inundated many lowland settings as ice retreated (Beaudoin et al., 1996). These lakes drained before and during the Paleoindian occupation of the region. The locations of Paleoindian sites, especially the earlier ones (i.e., Clovis), may have been dictated by the presence of these shrinking lakes. Thus, site locations shifted through time as the lake declined (Beaudoin and Lemmen, 2000, 39).

Dunes and loess

Eolian deposits and landforms are ubiquitous on the Great Plains owing to the open, windy environment, the semiarid climate, and the availability of easily erodible substrate. The deposits include sand in dune fields, lunettes, and sheets, and silt in primary and redeposited loess. Few Paleoindian sites are found within eolian deposits, but Holocene-age eolian sediments buried many sites on Pleistocene and older landscapes. Most were exposed by historic wind deflation of these eolian mantles. The sites suffer from wind erosion, exposure, and reburial (and perhaps several cycles of these processes) and, therefore, typically do not yield useful chronological or paleoecological data.

Dunes and sand sheets are common on the western side of the Southern High Plains, and lunettes border some of the larger playa basins (Holliday, 1997b, 2001; Rich et al., 1999). Paleoindian sites and collections of Paleoindian artifacts are relatively well known from the dune fields. Some of the dunes (e.g., at Shifting Sands and Winkler-1 in the Andrews Dunes; Table 5; Figure 1) rest on older (Clovis age or pre-Clovis age) lake and marsh deposits or other indicators of moist settings that could have attracted Paleoindian foragers.

Extensive deposits of loess and eolian sand cover the Central Great Plains (Muhs and Zarate, 2001; Bettis et al., 2003; Busacca et al., 2004). In some areas of Western Nebraska, the Pleistocene loess is more than 20 m thick. The Peoria Loess, which largely predates the Paleoindian occupation, is the most common Quaternary deposit on uplands of the Central Plains. Landscape stability and soil formation that occurred after aggradation of the Peoria Loess included Paleoindian time (Holliday, 1997a). In some areas of the Central Plains, especially on bluff tops adjacent to major rivers such as the Platte, Republican, and Arkansas, Bignell Loess mantles the Peoria Loess (Figure 6). Maximum limiting ages of the Bignell are based on radiocarbon ages determined on soil organic matter from the Brady Paleosol developed at the top of the Peoria Loess (Mason et al., 2006). These ages in combination with radiocarbon and luminescence ages determined on materials



Great Plains Geoarchaeology, Figure 6 Loess stratigraphy exposed at Bignell Hill overlooking the Platte River in Southwestern Nebraska. This is the type locality for the Bignell Loess and Brady Paleosol. The Brady Paleosol, which typically developed between ca. 15,500 and 9,000 years ago, represents a buried Paleoindian landscape that has yielded cultural deposits at other localities in the Central Plains. There is potential for Late Paleoindian and younger cultural deposits in the overlying Bignell Loess (Photo courtesy of Peter Jacobs).

Great Plains Geoarchaeology, Table 7 Selected rock-shelters on the Great Plains

Site	Setting	Geoarchaeology	References
Bonfire Shelter (Texas)	Mile Canyon, tributary to Rio Grande	Plainview/Folsom bison bone bed	Dibble and Lorrain, 1968; Bement, 1986; Robinson, 1997
Kincaid Shelter[a] (Texas)	Sabinal River (both shelter and terrace)	Clovis in spring and flood plain backwater fines and on stone "pavement"; Folsom (not in situ); Golondrina, Texas Angostura and San Patrice in midden deposits	Hester et al., 1985; Collins et al., 1989; Collins, 1990
Baker Cave (Texas)	Phillips Canyon, tributary to Devil's River	Golondrina occupation in fine midden debris	Word and Douglas, 1970; T. Hester, 1982
Charlie Lake Cave (British Columbia)	Peace River	Multiple occupations 10,500 (including fluted style)–9,500 year BP in slope wash below rock-shelter	Fladmark et al., 1988

[a]Kincaid also associated with floodplain

from the Bignell Loess indicate that the Bignell aggraded episodically throughout the Holocene (Mason and Kuzila, 2000; Mason et al., 2003, 2006). The Brady Paleosol, which typically developed between 15,500 and 9,000 years ago during a time of warming and drying (Feggestad et al., 2004; Mason et al., 2008), represents a buried Paleoindian landscape that has yielded cultural deposits. For example, at site 25KH67 in Western Nebraska along the South Platte River, a Paleoindian component that may represent a Hell Gap (ca. 10,000 year BP) or Agate Basin (10,500–10,000 year BP) occupation occurs in the lower Brady Paleosol (May and Holen, 2003).

Eolian sand on the Northern High Plains is largely in the form of dune fields, most notably the huge Nebraska Sand Hills, along with other dune systems from throughout the region (Figure 1) (Muhs and Zarate, 2001). Collections of Paleoindian artifacts are well known from these settings (see Holen, 1989; Holen and Hofman, 1999). The Wray Dunes in northeastern Colorado (Figure 1) produced large collections of Paleoindian artifacts during the

1920s and 1930s (Table 6), forming the basis for one of the first systematic studies of large Paleoindian collections. These assemblages were in the uppermost Peoria Loess, likely in the Brady soil, and exposed by deflation of the overlying sand dunes.

Thin deposits of eolian sand and silt are scattered across the Alberta Plains. Some eolian sedimentation was contemporaneous with Paleoindian occupation and is indicative of the unstable, recently deglaciated character of the region at the time. Most of the sites reported from the Alberta Plains are Late Paleoindian (mostly Cody), and several were exposed due to deflation of the eolian sands that encase them.

Rock-shelters

Rock-shelters on the Great Plains (Table 7) with documented Paleoindian records are almost exclusively on the Edwards Plateau, where they are ubiquitous owing to the thick, extensive, and karstified limestone (Collins, 1991, 1995). Debris of Archaic and later occupations is widespread in these settings, but reports of Paleoindian features are relatively uncommon (Dibble and Alexander, 1971; Collins, 1991). According to Collins (1991: Table 6.2), Paleoindian materials are reported from only 10 (~18 %) of 55 recorded rock-shelters.

Multiple Paleoindian occupations are known from Baker Cave, Horn Shelter, and Kincaid Shelter (Figure 1). They seem to be associated with fine-grained fill with a high percentage of midden debris (Table 2), though there are hints of coarser limestone spall dating to earlier Paleoindian or pre-Paleoindian times (e.g., Ross, 1965). Mixing, probably bioturbation, appears to be a significant problem in other shelters, e.g., Levi (see Alexander, 1963), confusing the artifact and radiocarbon associations (Bousman et al., 2004). The single component Paleoindian bone bed at Bonfire Shelter is associated with coarser fill.

Bibliography

Agogino, G. A., and Galloway, E., 1965. The Sister's Hill site: a Hell Gap site in north-central Wyoming. *Plains Anthropologist*, **10**(29), 190–195.

Agogino, G. A., and Parrish, A., 1971. The Fowler-Parrish site: a Folsom campsite in eastern Colorado. *Plains Anthropologist*, **16**(52), 111–114.

Ahler, S. A., 1986. *The Knife River Flint Quarries: Excavations at Site 32DU508*. Bismarck: State Historical Society of North Dakota.

Albanese, J., 1974. Geology of the casper archaeological site. In Frison, G. C. (ed.), *The Casper Site*. New York: Academic, pp. 174–190.

Albanese, J., 1977. Paleotopography and Paleoindian sites in Wyoming and Colorado. In Johnson, E. (ed.), *Paleoindian Lifeways. The Museum Journal*. Lubbock: West Texas Museum Association, Vol. 17, pp. 28–47.

Albanese, J., 1982. Geologic investigation. In Frison, G. C., and Stanford, D. J. (eds.), *The Agate Basin Site: A Record of the Paleoindian Occupation of the Northwestern High Plains*. New York: Academic, pp. 309–330.

Albanese, J., 1996. Geology of the Mill Iron site. In Frison, G. C. (ed.), *The Mill Iron Site*. Albuquerque: University of New Mexico Press, pp. 25–41.

Albanese, J., 2000. Resumé of geoarchaeological research on the northwestern Plains. In Mandel, R. D. (ed.), *Geoarchaeology in the Great Plains*. Norman: University of Oklahoma Press, pp. 199–249.

Alexander, H. L., Jr., 1963. The Levi site: a Paleo-Indian campsite in central Texas. *American Antiquity*, **28**(4), 510–528.

Amick, D. S., and Rose, R. O., 1990. Dimensioning Folsom variability: lessons from the shifting sands site. In Brothers, P. (ed.), *Transactions of the 25th Regional Archeological Symposium for Southeastern New Mexico and Western Texas*. Midland: Midland Archeological Society, pp. 1–24.

Artz, J. A., 1995. Geological contexts of the early and middle Holocene archeological record in North Dakota and adjoining areas of the northern Great Plains. In Bettis, E. A., III (ed.), *Archaeological Geology of the Archaic Period in North America*. Boulder: Geological Society of America. Special Paper 297, pp. 67–86.

Baker, W. E., Campbell, T. N., and Evans, G. L., 1957. The Nall site: evidence of early man in the Oklahoma panhandle. *Bulletin of the Oklahoma Anthropological Society*, **5**, 1–20.

Barbour, E. H., and Schultz, C. B., 1932. The Scottsbluff bison quarry and its artifacts. *The Nebraska State Museum Bulletin*, **34**(1), 283–286.

Barbour, E. H., and Schultz, C. B., 1936. Palaeontologic and geologic consideration of early man in Nebraska. *The Nebraska State Museum Bulletin*, **45**(1), 431–449.

Barbour, E. H., and Schultz, C. B., 1941. The lipscomb bison quarry, lipscomb county, Texas. *Bulletin of the University of Nebraska State Museum*, **2**(7), 67–68.

Beaudoin, A. B., and Lemmen, D. S. (eds.), 2000. *Late Quaternary History and Geoarchaeology of Southeastern Alberta and Southwestern Saskatchewan*. Calgary: GeoCanada. Field Trip Guidebook 3.

Beaudoin, A. B., Wright, M., and Ronaghan, B., 1996. Late quaternary landscape history and archaeology in the 'Ice-free Corridor': some recent results from Alberta. *Quaternary International*, **32**, 113–126.

Bement, L. C., 1986. *Excavation of the Late Pleistocene Deposits of Bonfire Shelter, 41VV218, Val Verde County, Texas, 1983–1984*. Austin: Texas Archeological Survey, The University of Texas at Austin. Archeology Series 1.

Bettis, E. A., III, Muhs, D. R., Roberts, H. M., and Wintle, A. G., 2003. Last Glacial loess in the conterminous USA. *Quaternary Science Reviews*, **22**(18–19), 1907–1946.

Bousman, C. B., 1998. Late Paleoindian archeology. In Collins, M. B. (ed.), *Wilson-Leonard: An 11,000-year Archeological Record of Hunter-Gatherers in Central Texas; Volume I: Introduction, Background, and Synthesis*. Austin: Texas Archeological Research Laboratory, University of Texas at Austin; Texas Department of Transportation, Environmental Affairs Division. Studies in Archeology 31, pp. 161–210. Report 10.

Bousman, C. B., Collins, M. B., Goldberg, P., Stafford, T., Guy, J., Baker, B. W., Steele, D. G., Kay, M., Kerr, A., Fredlund, G., Dering, P., Holliday, V., Wilson, D., Gose, W., Dial, S., Takac, P., Balinsky, R., Masson, M., and Powell, J. P., 2002. The Palaeoindian-Archaic transition in North America: new evidence from Texas. *Antiquity*, **76**(294), 980–990.

Bousman, C. B., Baker, B. W., and Kerr, A. C., 2004. Paleoindian archaeology in Texas. In Perttula, T. (ed.), *The Prehistory of Texas*. College Station: Texas A&M University Press, pp. 15–97.

Brunswig, R. H., 2007. New interpretations of the Dent mammoth site: a synthesis of recent multidisciplinary evidence. In Brunswig, R. H., and Pitblado, B. L. (eds.), *Frontiers in*

Colorado Paleoindian Archaeology. Boulder: University Press of Colorado, pp. 87–121.

Brunswig, R. H., and Fisher, D. C., 1993. Research on the Dent Mammoth site. *Current Research in the Pleistocene*, **10**, 63–65.

Bryan, K., and Ray, L. L., 1940. *Geologic Antiquity of the Lindenmeier Site in Colorado*. Washington, DC: Smithsonian Institution. Smithsonian Miscellaneous Collections 99, no. 2.

Busacca, A. J., Begét, J. E., Markewich, H. W., Muhs, D. R., Lancaster, N., and Sweeney, M. R., 2004. Eolian sediments. In Gillespie, A. R., Porter, S. C., and Atwater, B. F. (eds.), *The Quaternary Period in the United States*. New York: Elsevier. Developments in Quaternary Science 1, pp. 275–309.

Clayton, L., Moran, S. R., and Bickley, W. B., Jr., 1976. *Stratigraphy, Origin, and Climatic Implications of Late Quaternary Upland Silt in North Dakota*. Pierre: North Dakota Geological Survey. Miscellaneous Series 54.

Collins, M. B., 1990. The archaeological sequence at Kincaid Rockshelter, Uvalde County, Texas. In Brothers, P. (ed.), *Transactions of the 25th Regional Archeological Symposium for Southeastern New Mexico and Western Texas*. Midland: Midland Archeological Society, pp. 25–33.

Collins, M. B., 1991. Rockshelters and the early archaeological record in the Americas. In Dillehay, T. D., and Meltzer, D. J. (eds.), *The First Americans: Search and Research*. Boca Raton: CRC Press, pp. 157–182.

Collins, M. B., 1995. Forty years of archeology in central Texas. *Bulletin of the Texas Archeological Society*, **66**, 361–400.

Collins, M. B. (ed.), 1998a. *Wilson-Leonard: An 11,000-year Archeological Record of Hunter-Gatherers in Central Texas*. Austin: Texas Archeological Research Laboratory, University of Texas at Austin; Texas Department of Transportation, Environmental Affairs Division. Studies in Archeology 31. Report 10 (in 5 volumes).

Collins, M. B., 1998b. Early Paleoindian components. In Collins, M. B. (ed.), *Wilson-Leonard: An 11,000-year Archeological Record of Hunter-Gatherers in Central Texas; Volume I: Introduction, Background, and Synthesis*. Austin: Texas Archeological Research Laboratory, University of Texas at Austin; Texas Department of Transportation, Environmental Affairs Division. Studies in Archeology 31, pp. 123–159. Report 10.

Collins, M. B., and Brown, K. M., 2000. The gault gisement: some preliminary observations. *Current Archeology in Texas*, **2**(1), 8–11.

Collins, M. B., Evans, G. L., Campbell, T. N., Winans, M. C., and Mear, C. E., 1989. Clovis occupation at Kincaid shelter, Texas. *Current Research in the Pleistocene*, **6**, 3–4.

Cordova, C. E., Johnson, W. C., Mandel, R. D., and Palmer, M. W., 2011. Late Quaternary environmental change inferred from phytoliths and other soil-related proxies: Case studies from the central and southern Great Plains, USA. *Catena*, **85**(2), 87–108.

Davis, E. M., 1953. Recent data from two Paleo-Indian sites on Medicine Creek, Nebraska. *American Antiquity*, **18**(4), 380–386.

Davis, E. M., 1962. *Archeology of the Lime Creek Site in Southwestern Nebraska*. Lincoln: University of Nebraska State Museum. Special Publication of the University of Nebraska State Museum 3.

Dibble, D. S., and Alexander, R. K., 1971. The archeology of Texas caves. In Lundelius, E. L., Jr., and Slaughter, B. H. (eds.), *Natural History of Texas Caves*. Dallas: Gulf Natural History, pp. 133–148.

Dibble, D. S., and Lorrain, D., 1968. *Bonfire Shelter: A Stratified Bison Kill Site, Val Verde County, Texas*. Austin: Texas Memorial Museum, University of Texas. Miscellaneous Papers 1.

Dick, H. W., and Mountain, B., 1960. The Claypool site: a cody complex site in northeastern Colorado. *American Antiquity*, **26**(2), 223–235.

Donahue, J., and Sellet, F., 2002. The chronology of the Goshen Bone Bed at the Jim Pitts site. *Current Research in the Pleistocene*, **19**, 128–129.

Ebell, S. B., 1988. The Dunn site. *Plains Anthropologist*, **33**(122), 505–530.

Fedje, D. W., 1986. Banff archaeology: 1983–1985. In Ronaghan, B. (ed.), *Eastern Slopes Prehistory: Selected Papers*. Edmonton: Archaeological Survey of Alberta. Occasional Paper 30, pp. 25–62.

Fedje, D. W., White, J. M., Wilson, M. C., Nelson, D. E., Vogel, J. S., and Southon, J. S., 1995. Vermilion Lakes site: adaptations and environments in the Canadian rockies during the latest Pleistocene and early Holocene. *American Antiquity*, **60**(1), 81–108.

Feggestad, A. J., Jacobs, P. M., Miao, X., and Mason, J. A., 2004. Stable carbon isotope record of Holocene environmental change in the central Great Plains. *Physical Geography*, **25**(2), 170–190.

Fenneman, N. M., 1931. *Physiography of Western United States*. New York: McGraw-Hill.

Ferring, C. R., 2001. *Archaeology and Paleoecology of the Aubrey Clovis Site (41DN479) Denton County, Texas*. Fort Worth: US. Army Corps of Engineers, Fort Worth District.

Fladmark, K. R., Driver, J. C., and Alexander, D., 1988. The Paleoindian component at Charlie Lake Cave (HbRf 39), British Columbia. *American Antiquity*, **53**(2), 371–384.

Forbis, R. G., 1968. Fletcher: a Paleo-Indian site in Alberta. *American Antiquity*, **33**(1), 1–10.

Frison, G. C., 1974. *The Casper Site: A Hell Gap Bison Kill on the High Plains*. New York: Academic.

Frison, G. C., 1976. The chronology of Paleoindian and Altithermal Period groups in the Bighorn Basin, Wyoming. In Cleveland, C. E. (ed.), *Cultural Change and Continuity: Essays in Honor of James Bennett Griffin*. New York: Academic, pp. 147–173.

Frison, G. C., 1984. The Carter/Kerr-McGee Paleoindian site: cultural resource management and archaeological research. *American Antiquity*, **49**(2), 288–314.

Frison, G. C. (ed.), 1996. *The Mill Iron Site*. Albuquerque: University of New Mexico Press.

Frison, G. C., 1998. Paleoindian large mammal hunters on the plains of North America. *Proceedings of the National Academy of Sciences*, **95**(24), 14576–14583.

Frison, G. C., and Stanford, D. J. (eds.), 1982. *The Agate Basin Site: A Record of the Paleoindian Occupation of the Northwestern High Plains*. New York: Academic.

Gebhard, P. H., 1949. An archaeological survey of the Blowouts of Yuma County, Colorado. *American Antiquity*, **15**(2), 132–143.

Gillespie, J. D., 2002. *Archaeological and Geological Evidence for the First Peopling of Alberta*. M.A. thesis, University of Calgary.

Gryba, E. M., 1983. *Sibbald Creek: 11,000 Years of Human Use of the Alberta Foothills*. Edmonton: Archaeological Survey of Alberta. Occasional Paper 22.

Hartwell, W. T., 1995. The Ryan's site cache: comparisons to plainview. *Plains Anthropologist*, **40**(152), 165–184.

Haynes, C. V., Jr., 1975. Pleistocene and recent stratigraphy. In Wendorf, F., and Hester, J. J. (eds.), *Late Pleistocene Environments of the Southern High Plains*. Taos: Fort Burgwin Research Center. Publication 9, pp. 57–96.

Haynes, C. V., Jr., 1995. Geochronology of paleoenvironmental change, Clovis type site, Blackwater Draw, New Mexico. *Geoarchaeology*, **10**(5), 317–388.

Haynes, C. V., Jr., and Agogino, G. A., 1960. *Geological Significance of a New Radiocarbon Date from the Lindenmeier Site*. Denver: The Denver Museum of Natural History. Proceedings 9.

Haynes, C. V., Jr., and Agogino, G. A., 1966. Prehistoric springs and geochronology of the Clovis site, New Mexico. *American Antiquity*, **31**(6), 812–821.

Haynes, C. V., Jr., and Grey, D. C., 1965. The Sister's Hill site and its bearing on the Wyoming postglacial alluvial chronology. *Plains Anthropologist*, **10**(29), 196–211.

Haynes, C. V., Jr., McFaul, M., Brunswig, R. H., and Hopkins, K. D., 1998. Kersey-Kuner terrace investigations at the Dent and Bernhardt sites, Colorado. *Geoarchaeology*, **13**(2), 01–218.

Hester, J. J., 1962. A Folsom lithic complex from the Elida site, Roosevelt County, N. M. *El Palacio*, **69**(2), 92–113.

Hester, J. J., 1975. The sites. In Wendorf, F., and Hester, J. J. (eds.), *Late Pleistocene Environments of the Southern High Plains*. Taos: Fort Burgwin Research Center. Publication 9, pp. 13–32.

Hester, T. R., 1982. Late Paleo-Indian occupations at Baker Cave, Southwestern Texas. *Bulletin of the Texas Archeological Society*, **53**, 101–119.

Hester, T. R., Evans, G. L., Asaro, F., Stross, F., Campbell, T. N., and Michel, H., 1985. Trace element analysis of an obsidian Paleo-Indian projectile point from Kincaid Rockshelter, Texas. *Bulletin of the Texas Archeological Society*, **56**, 143–153.

Hill, M. E., Jr., 2002. The Milnesand site: site formation study of a Paleoindian bison bonebed in eastern New Mexico. *Plains Anthropologist*, **47**(183), 323–337.

Hill, M. G., Holliday, V. T., and Stanford, D. J., 1995. A further evaluation of the San Jon site, New Mexico. *Plains Anthropologist*, **40**(150), 369–390.

Hill, M. G., Hill, M. E., Jr., May, D. W., Myers, T. P., Rapson, D. J., Sellet, F., Theler, J. L., and Todd, L. C., 2002a. Paleoindian subsistence behavior at the Clary Ranch site, Nebraska, USA. *Antiquity*, **76**(292), 311–312.

Hill, M. G., Hill, M. E., Jr., May, D. W., Myers, T. P., Rapson, D. J., Sellet, F., Theler, J. L., and Todd, L. C., 2002b. 2001 investigations at the Clary Ranch site, Nebraska. *Current Research in the Pleistocene*, **19**, 32–34.

Hofman, J. L., 1995. Dating Folsom occupations on the Southern high plains: the Lipscomb and Waugh sites. *Journal of Field Archaeology*, **22**(4), 421–437.

Hofman, J. L., Amick, D. S., and Rose, R. O., 1990. Shifting sands: a Folsom-midland assemblage from a campsite in western Texas. *Plains Anthropologist*, **35**(129), 221–253.

Hofman, J. L., Hill, M. E., Jr., Johnson, W. C., and Sather, D. T., 1995. Norton: an early-Holocene bison bone bed in western Kansas. *Current Research in the Pleistocene*, **12**, 19–21.

Holen, S. R., 1989. Anthropology: the native American occupation of the Sand Hills. In Bleed, A. S., and Flowerday, C. (eds.), *An Atlas of the Sand Hills*. Lincoln: Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln. University of Nebraska Conservation and Survey Division Resource Atlas Number 5, pp. 189–205.

Holen, S. R., and Hofman, J. L., 1999. Folsom evidence from the Nebraska Sand Hills: the Elfgren site. *Current Research in the Pleistocene*, **16**, 38–40.

Holliday, V. T., 1985. Archaeological geology of the Lubbock Lake site, Southern High Plains of Texas. *Geological Society of America Bulletin*, **96**(12), 1483–1492.

Holliday, V. T., 1987. Geoarchaeology and late quaternary geomorphology of the middle South Platte river, northeastern Colorado. *Geoarchaeology*, **2**(4), 317–329.

Holliday, V. T., 1995. *Stratigraphy and Paleoenvironments of Late Quaternary Valley Fills on the Southern High Plains*. Boulder: Geological Society of America. Memoir 186.

Holliday, V. T., 1997a. *Paleoindian Geoarchaeology of the Southern High Plains*. Austin: University of Texas Press.

Holliday, V. T., 1997b. Origin and evolution of lunettes on the high plains of Texas and New Mexico. *Quaternary Research*, **47**(1), 54–69.

Holliday, V. T., 2001. Stratigraphy and geochronology of upper quaternary eolian sand on the Southern high plains of Texas and New Mexico, United States. *Geological Society of America Bulletin*, **113**(1), 88–108.

Holliday, V. T., and Allen, B. L., 1987. Geology and soils. In Johnson, E. M. (ed.), *Lubbock Lake: Late Quaternary Studies on the Southern High Plains*. College Station: Texas A&M University Press, pp. 14–21.

Holliday, V. T., and Mandel, R. D., 2006. Paleoindian geoarchaeology of the Great Plains, Central Lowlands, and Southwestern U.S. In Ubelaker, D. H. (ed.), *Environment, Origins, and Population, volume 3: Handbook of North American Indians*. Washington, DC: Smithsonian Institution Press, pp. 23–46.

Holliday, V. T., Haynes, C. V., Jr., Hofman, J. L., and Meltzer, D. J., 1994. Geoarchaeology and geochronology of the Miami (Clovis) site, Southern High Plains of Texas. *Quaternary Research*, **41**(2), 234–244.

Holliday, V. T., Johnson, E., and Stafford, T. W., 1999. AMS radiocarbon dating of the Plainview and Firstview (Paleoindian) type assemblages. *American Antiquity*, **64**(3), 444–454.

Holliday, V. T., Knox, J. C., Running, G. L., IV, Mandel, R. D., and Ferring, C. R., 2002. The Central Lowlands and Great Plains. In Orme, A. R. (ed.), *The Physical Geography of North America*. New York: Oxford University Press, pp. 335–362.

Irwin-Williams, C., Irwin, H. T., Agogino, G. A., and Haynes, C. V., 1973. Hell Gap: Paleo-Indian occupation on the High Plains. *Plains Anthropologist*, **18**(59), 40–53.

Johnson, E. M. (ed.), 1987. *Lubbock Lake: Late Quaternary Studies on the Southern High Plains*. College Station: Texas A&M University Press.

Joyes, D. C., 2000. Cody technology at the McLeod site, Saskatchewan, Canada. *Current Research in the Pleistocene*, **17**, 47–49.

Judson, S., 1953. *Geology of the San Jon Site, Eastern New Mexico*. Washington, DC: Smithsonian Institution. Smithsonian Miscellaneous Collection 121, no. 1.

Knudson, R., 2013. The Scottsbluff Bison Quarry site: its place in the Cody Complex. In Knell, E. J., and Muñiz, M. P. (eds.), *Paleoindian Lifeways of the Cody Complex*. Salt Lake City: University of Utah Press, pp. 290–314.

Kooyman, B., Newman, M. E., Cluney, C., Lobb, M., Tolman, S., McNeil, P., and Hills, L. V., 2001. Identification of horse exploitation by Clovis hunters based on protein analysis. *American Antiquity*, **66**(4), 686–691.

Kooyman, B., Hills, L. V., McNeil, P., and Tolman, S., 2006. Late Pleistocene horse hunting at the Wally's Beach site (DhPg-8), Canada. *American Antiquity*, **71**(1), 101–121.

Kornfeld, M., 2005. *Hell Gap Site. Cheyenne, Wyoming: Wyoming State Historic Preservation Office*. http://wyoshpo.state.wy.us/AAMonth/Poster.aspx?ID=7

LaBelle, J. M., 2002. Slim arrow, the long-forgotten Yuma-type site in eastern Colorado. *Current Research in the Pleistocene*, **19**, 52–55.

LaBelle, J. M., Holliday, V. T., and Meltzer, D. J., 2003. Early Holocene Paleoindian deposits at Nall Playa, Oklahoma panhandle. *Geoarchaeology*, **18**(1), 5–34.

Larson, M. L., Kornfeld, M., and Frison, G. C. (eds.), 2009. *Hell Gap: A Stratified Paleoindian Campsite at the Edge of the Rockies*. Salt Lake City: University of Utah Press.

Linnamae, U., 1998. *The Heron Eden Site in the Northern Plains Paleoindian World*. Paper presented at the Annual Conference of the Canadian Archaeological Association, Victoria, BC.

Litwinionek, L., Johnson, E., and Holliday, V. T., 2003. The playas of the Southern High Plains: an archipelago of human occupation for 12,000 years on the North American grasslands. In Kornfeld, M., and Osborn, A. J. (eds.), *Islands on the Plains: Ecological, Social, and Ritual Use of Landscapes*. Salt Lake City: The University of Utah Press, pp. 21–43.

Malde, H. E., 1960. Geological age of the Claypool site, northeastern Colorado. *American Antiquity*, **26**(2), 236–243.

Malde, H. E., 1984. Geology of the Frazier site, Kersey, Colorado. In Anderson, A. B. (ed.), *Paleoindian Sites of the Colorado Piedmont*. Boulder: American Quaternary Association Field Trip Guidebook, pp. 13–16.

Mandel, R. D., 2014. Investigations at the Coffey Site (14PO1), northeastern Kansas. In Mandel, R. D. (comp.), *Odyssey Research Program Report of Investigations*. Lawrence: Kansas Geological Survey, pp. 3–54.

Mandel, R. D. (ed.), 2000. *Geoarchaeology in the Great Plains*. Norman: University of Oklahoma Press.

Mandel, R. D., 2006. The effects of late quaternary landscape evolution on the archaeology of Kansas. In Hoard, R. J., and Banks, W. E. (eds.), *Kansas Archaeology*. Lawrence: University Press of Kansas, pp. 46–75.

Mandel, R. D., and Hofman, J. L., 2003. Geoarchaeological investigations at the Winger site: a late Paleoindian bison bonebed in southwestern Kansas, U.S.A. *Geoarchaeology*, **18**(1), 129–144.

Mandel, R. D., and Hofman, J. L., 2006. Simshauser site (15KY102) and Mattox Draw. In Mandel, R. D. (ed.), *Guidebook of the 18th Biennial Meeting of the American Quaternary Association*. Technical Series 21. Lawrence: Kansas Geological Survey, University of Kansas, pp. 4-9–4-16.

Mandel, R. D., Hofman, J. L., Holen, S., and Blackmar, J. M., 2004. Buried Paleo-Indian landscapes and sites on the High Plains of northwestern Kansas. In Nelson, E. P., and Erslev, E. A. (eds.), *Field Trips in the Southern Rocky Mountains, USA*. Boulder: The Geological Society of America. Geological Society of America Field Guide 5, pp. 69–88.

Mandel, R. D., Widga, C., Hofman, J. L., Ryan, S., and Bruner, K., 2006. The Claussen Site (14WB322). In Mandel, R. D. (ed.), *Guidebook of the 18th Biennial Meeting of the American Quaternary Association*. Lawrence: Kansas Geological Survey, University of Kansas. Technical Series 21, pp. 4-2–4-8. 4–8.

Mandel, R. D., Jacob, J. S., and Nordt, L. C., 2007. Geoarchaeology of the Richard Beene site. In Thoms, A. V., and Mandel, R. D. (eds.), *Archaeological and Paleoecological Investigations at the Richard Beene Site (41BX831), South Central Texas*. College Station: Texas A&M University. Center for Ecological Archaeology, Reports of Investigations, no. 8, pp. 27–60.

Mandel, R. D., Cordova, C. E., and Theler, J. L., 2009. The paleoenvironmental context of Paleoindian occupation in the central Great Plains of Kansas: a tale of two sites. *Geological Society of America*, **41**(7), 257. Abstracts with Programs.

Mandel, R. D., McLean, J. A., Ryan, S. R., Potter, A. R., and Kessler, N. V., 2010. *Geoarchaeological Investigation and Condition Assessment of the Coffey Site (14PO1), Tuttle Creek Lake, Pottawatomie County, Kansas.* Prepared for the Kansas City District of the U.S. Army Corps of Engineers by the Kansas Geological Survey and R. Christopher Goodwin & Associates, Inc., Lawrence, Kansas.

Mandel, R. D., Murphy, L. R., and Mitchell, M. D., 2014. Geoarchaeology and paleoenvironmental context of the Beacon Island site, an Agate Basin (Paleoindian) bison kill in northwestern North Dakota, USA. *Quaternary International*, **342**, 91–113.

Mason, J. A., and Kuzila, M. S., 2000. Episodic Holocene loess deposition in central Nebraska. *Quaternary International*, **67**(1), 119–131.

Mason, J. A., Jacobs, P. M., Hanson, P. R., Miao, X., and Goble, R. J., 2003. Sources and paleoclimatic significance of Holocene Bignell Loess, central Great Plains, USA. *Quaternary Research*, **60**(3), 330–339.

Mason, J. A., Bettis, E. A., III, Roberts, H. M., Muhs, D. R., and Joeckel, R. M., 2006. Last Glacial loess sedimentary system of eastern Nebraska and western Iowa. In Mandel, R. D. (ed.), *Guidebook of the 18th Biennial Meeting of the American Quaternary Association*. Lawrence: Kansas Geological Survey, University of Kansas. Technical Series 21, pp. 1-1–1-22.

Mason, J. A., Miao, X., Hanson, P. R., Johnson, W. C., Jacobs, P. M., and Goble, R. J., 2008. Loess record of the Pleistocene-Holocene transition on the northern and central Great Plains, USA. *Quaternary Science Reviews*, **27**(17–18), 1772–1783.

May, D. W., 2002. Stratigraphic studies at Paleoindian sites around Medicine Creek Reservoir. In Roper, D. C. (ed.), *Medicine Creek: Seventy Years of Archaeological Investigations*. Tuscaloosa: The University of Alabama Press, pp. 37–53.

May, D. W., and Holen, S. R., 2003. Eolian and soil stratigraphy at a Paleoindian site along the South Platte River valley, Nebraska, U.S.A. *Geoarchaeology*, **18**(1), 145–159.

May, D. W., and Holen, S. R., 2014. Early Holocene alluvial stratigraphy, chronology, and Paleoindian/early Archaic geoarchaeology in the Loup River Basin, Nebraska, U.S.A. *Quaternary International*, **342**, 73–90.

May, D. W., Hill, M. G., Holven, A. C., Loebel, T. J., Rapson, D. J., Semken, H. A., Jr., and Theler, J. L., 2008. Geoarchaeology of the Clary Ranch Paleoindian sites, Western Nebraska. In Raynolds, R. G. (ed.), *Roaming the Rocky Mountains and Environs: Geological Field Trips*. Boulder: The Geological Society of America. Field Guide 10, pp. 265–293.

McFaul, M., Traugh, K. L., Smith, G. D., and Doering, W., 1994. Geoarchaeologic analysis of South Platte River terraces: Kersey, Colorado. *Geoarchaeology*, **9**, 345–374.

Meltzer, D. J., 2006. *Folsom: New Archaeological Investigations of a Classic Paleoindian Bison Kill*. Berkeley: University of California Press.

Meltzer, D. J., Todd, L. C., and Holliday, V. T., 2002. The Folsom (Paleoindian) type site: past investigations, current studies. *American Antiquity*, **67**(1), 5–36.

Metcalf, M. D., and Ahler, S. A. (eds.), 1995. *Alkali Creek: A Stratified Record of Prehistoric Flint Mining in North Dakota*. Eagle: Metcalf Archaeological Consultants.

Meyer, D., 1985. A component in the Scottsbluff tradition: excavations at the Niska site. *Canadian Journal of Archaeology*, **9**(1), 1–37.

Meyer, D., and Liboiron, H., 1990. A Paleoindian drill from the Niska site in southern Saskatchewan. *Plains Anthropologist*, **35**(129), 299–302.

Muhs, D. R., and Zarate, M., 2001. Late quaternary eolian record of the Americas and their paleoclimatic significance. In Markgraf, V. (ed.), *Interhemispheric climate linkages*. San Diego: Academic, pp. 183–216.

Myers, T. P., Corner, R. G., and Tanner, L. G., 1981. Preliminary report on the 1979 excavations at the Clary Ranch site. *Transactions of the Nebraska Academy of Sciences*, **9**, 1–7.

Ray, J. H., and Mandel, R. D., 2014. Investigations at the Coffey Site (14PO1), northeastern Kansas. In Mandel, R. D. (comp.), *Odyssey Research Program Report of Investigations*. Lawrence: Kansas Geological Survey, pp. 3–54.

Reider, R. G., 1980. Late Pleistocene and Holocene soils of the Carter/Kerr-McGee archeological site, Powder River Basin, Wyoming. *Catena*, **7**(4), 301–315.

Reider, R. G., 1982. Soil development and paleoenvironments. In Frison, G. C., and Stanford, D. J. (eds.), *The Agate Basin Site: A Record of the Paleoindian Occupation of the Northwestern High Plains*. New York: Academic, pp. 331–344.

Reider, R. G., 1983. Soils and Late Pleistocene-Holocene Environments of the Sister's Hill Archeological Site Near Buffalo, Wyoming. University of Wyoming Contributions to Geology, Laramie: University of Wyoming, **22**(2), 117–127.

Reider, R. G., 1990. Late Pleistocene and Holocene pedogenic and environmental trends at archaeological sites in plains and mountain areas of Colorado and Wyoming. In Lasca, N. P., and Donahue, J. (eds.), *Archaeological Geology of North America*. Boulder: Geological Society of America. Centennial Special, Vol. 4, pp. 335–360.

Reider, R. G., 1996. Soils and geomorphic surfaces of the Mill Iron site. In Frison, G. C. (ed.), *The Mill Iron Site*. Albuquerque: University of New Mexico Press, pp. 195–204.

Renaud, E. B., 1931. *Prehistoric Flaked Points from Colorado and Neighboring Districts*. Denver: Colorado Museum of Natural History. Proceedings 10, no. 2.

Renaud, E. B., 1932. *Yuma and Folsom Artifacts (New Material)*. Denver: Colorado Museum of Natural History. Proceedings 11, no. 2.

Rich, J., Stokes, S., and Wood, W. W., 1999. Holocene chronology for lunette dune deposition on the Southern High Plains, USA. *Zeitschrift für Geomorphologie, Supplementbände*, **116**, 165–180.

Roberts, F. H. H., 1937. New developments in the problem of the Folsom complex. *Explorations and Field-Work of the Smithsonian Institution in 1936*, pp. 69–74.

Roberts, F. H. H., 1940. Developments in the problem of the North American paleo-Indian. In Nichols, F. S. (ed.), *Essays in Historical Anthropology of North America*. Washington, DC: Smithsonian Institution. Smithsonian Miscellaneous Collections 100, pp. 51–116.

Roberts, F. H. H., 1942. *Archeological and Geological Investigations in the San Jon District, Eastern New Mexico*. Washington, DC: Smithsonian Institution. Smithsonian Miscellaneous Collections 103, no. 4.

Robinson, D. G., 1997. Stratigraphic analysis of bonfire shelter, southwest Texas: pilot studies of depositional processes and paleoclimate. *Plains Anthropologist*, **42**(152), 33–43. Memoir 29.

Ronaghan, B., 1993. The James Pass project: early Holocene occupation in the front ranges of the rocky mountains. *Canadian Journal of Archaeology*, **17**, 85–91.

Root, M. J. (ed.), 2000. *The Archaeology of the Bobtail Wolf Site: Folsom Occupation of the Knife River Flint Quarry Area, North Dakota*. Pullman: Washington State University Press. Contributions in Cultural Resource Management 61.

Root, M. J., Ahler, S. A., VanNest, J., Falk, C. R., and Foss, J. E., 1985. *Archaeological Investigations in the Knife River Flint Primary Source Area, Dunn County, North Dakota: The Benz Site, 32DU452*. Grand Forks: University of North Dakota. Department of Anthropology Contribution 225.

Roper, D. C. (ed.), 2002. *Medicine Creek: Seventy Years of Archaeological Investigations*. Tuscaloosa: The University of Alabama Press.

Ross, R. E., 1965. *The Archeology of Eagle Cave*. Austin: The University of Texas. Texas Archeological Salvage Project Paper 7.

Schmits, L. J., 1980. Holocene fluvial history and depositional environments at the Coffey site, Kansas. In Johnson, A. E. (ed.), *Archaic Prehistory on the Prairie-Plains Border*. Lawrence: University of Kansas. Publications in Anthropology no. 12, pp. 79–106.

Schultz, C. B., and Eiseley, L., 1935. Paleontological evidence for the antiquity of the Scottsbluff Bison Quarry and its associated artifacts. *American Anthropologist*, **37**(2), 306–319.

Sellards, E. H., 1938. Artifacts associated with fossil elephant. *Geological Society of America Bulletin*, **49**(7), 999–1010.

Sellards, E. H., 1955. Fossil bison and associated artifacts from Milnesand, New Mexico. *American Antiquity*, **20**(4), 336–344.

Sellet, F., 2001. A changing perspective on Paleoindian chronology and typology: a view from the northwestern plains. *Arctic Anthropology*, **38**(2), 48–63.

Sellet, F., Donohue, J., and Hill, M. G., 2009. The Jim Pitts site: a stratified Paleoindian site in the Black Hills of South Dakota. *American Antiquity*, **74**(4), 735–758.

Stafford, T. W., Jr., 1981. Alluvial geology and archaeological potential of the Texas Southern High Plains. *American Antiquity*, **46**(3), 548–565.

Stanford, D., 1978. The Jones-Miller site: an example of hell gap bison procurement strategy. In Davis, L. B., and Wilson, M. C. (eds.). *Bison Procurement and Utilization: A Symposium. Plains Anthropologist*, 23(82, pt 2; Memoir 14): 90–97.

Stanford, D., 1979. The Selby and Dutton sites: evidence for a possible pre-clovis occupation of the High Plains. In Humphrey, R. L., and Stanford, D. (eds.), *Pre-Llano Cultures of the Americas: Paradoxes and Possibilities*. Washington, DC: The Anthropological Society of Washington, pp. 101–123.

Stanford, D., 1984. The Jones-Miller site: a study of Hell Gap bison procurement and processing. *National Geographic Society Research Reports, 1975 Projects*, **16**, 615–635.

Stanford, D., and Albanese, J., 1975. Preliminary results of the Smithsonian Institution excavation at the Claypool site, Washington County, Colorado. *Southwestern Lore*, **41**, 22–28.

Thoms, A. V., and Mandel, R. D. (eds.), 2007. *Archaeological and Paleoecological Investigations at the Richard Beene Site (41BX831), South Central Texas*. College Station: Texas A&M University. Center for Ecological Archaeology, Reports of Investigations no. 8.

Van Nest, J., 1995. Geology of the Alkali Creek site. In Metcalf, M. D., and Ahler, S. A. (eds.), *Alkali Creek: A Stratified Record of Prehistoric Flint Mining in North Dakota*. Eagle: Metcalf Archaeological Consultants, pp. 51–109.

Vickers, J. R., and Beaudoin, A. B., 1989. A limiting AMS date for the Cody Complex occupation at the Fletcher site, Alberta, Canada. *Plains Anthropologist*, **34**(125), 261–264.

Warnica, J. M., 1961. The Elida site: evidence of a Folsom occupation in Roosevelt county, eastern New Mexico. *Bulletin of the Texas Archeological Society*, **30**, 209–215.

Warnica, J. M., and Williamson, T., 1968. The Milnesand site – revisited. *American Antiquity*, **33**(1), 16–24.

Wheat, J. B., 1972. *The Olsen-Chubbuck Site: A Paleo-Indian Bison Kill*. Washington, DC: Society for American Archaeology. Society for American Archaeology Memoir 26.

Wheat, J. B., 1979. *The Jurgens Site*. Lincoln: Plains Anthropologist. Plains Anthropologist Memoir 15.

William, J. D. (ed.), 2000. *The Big Black Site (32DU955C): A Folsom Complex Workshop in the Knife River Flint Quarry Area, North Dakota*. Pullman: Washington State University Press.

Wilmsen, E. M., and Roberts, F. H. H., Jr., 1978. *Lindenmeier, 1934–1974: Concluding Report of Investigations*. Washington, DC: Smithsonian Institution. Smithsonian Contributions to Anthropology 24.

Wishart, D. J. (ed.), 2011. *Encyclopedia of the Great Plains*. Lincoln: University of Nebraska Press.

Wood, W. R. (ed.), 1998. *Archaeology on the Great Plains*. Lawrence: University Press of Kansas.

Word, J. H., and Douglas, C. L., 1970. *Excavations at Baker Cave, Val Verde County, Texas: The Archeological Investigation*. Austin: The University of Texas. Texas Memorial Museum Bulletin 16.

Zier, C. J., Jepson, D. A., McFaul, M., and Doering, W., 1993. Archaeology and geomorphology of the Clovis-age Klein site near Kersey, Colorado. *Plains Anthropologist*, **38**(143), 203–210.

GRIMALDI CAVES

Francesco G. Fedele
Formerly University of Naples ‘Federico II’, Naples, Torino, Italy

Synonyms

Balzi Rossi (Italian for “red cliffs”); Grottes de Menton (France)

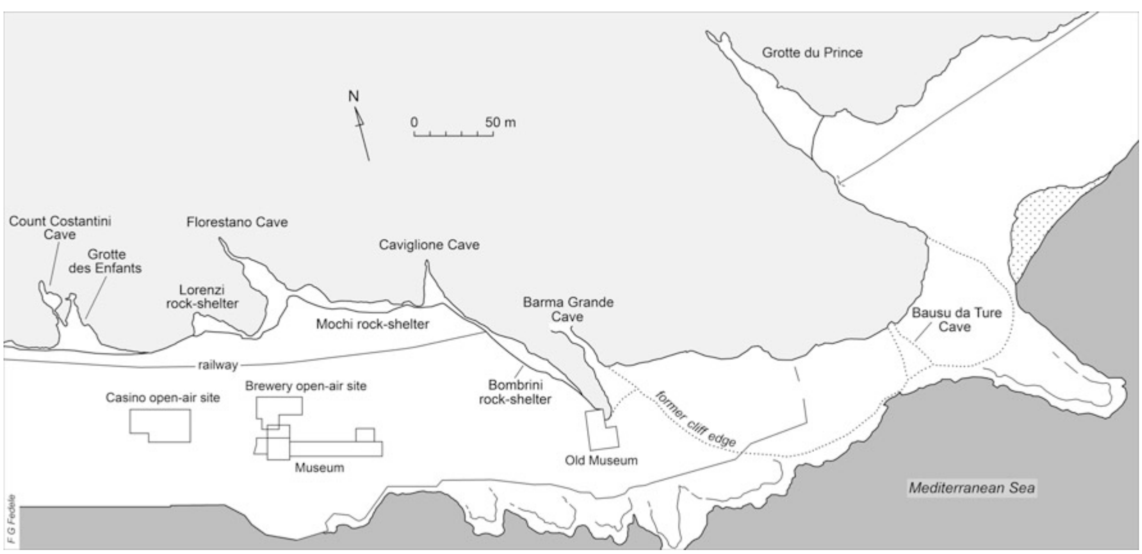
Definition

The Grimaldi caves include a group of 15 caves and rock shelters in coastal cliffs 5 km west of Ventimiglia near the French-Italian border, Liguria, Italy (Figure 1). The geographical coordinates are 43°47′ N and 7°32′ E, and the sites lie at 8–15 m asl.

Due to a combination of rocky coast, deeply stratified deposits, and cultural occupation, Grimaldi represents an important locality for both coastal geoarchaeology and Paleolithic studies in Europe. Steep seaward slopes descend from mountain ridges nearby, and the indented, plunging cliff coast is carved into Jurassic limestone. Tidal notches developed during major sea level stands, the present one associated with an intertidal shore platform in a staircase formed by Pleistocene marine terraces (Furlani et al., 2014, 96–97). Two Paleolithic open-air sites on the platform in front of the cave complex have been recognized.

Overall, the Grimaldi sedimentary sequences span an interval from 300 to 200 ka BP to the present, with the Marine Isotope Stage (MIS) 5 interglacial transgression and the subsequent glacial best represented within the deposits. An interesting cultural-ecological aspect, due to the high coastal relief, is the unusual stability of the marine habitats through time; this greatly reduces the two most common causes of noncultural variation in sea resource procurement – species biogeography and reconfiguration of shoreline habitats – allowing for human foraging agendas to be better assessed (Stiner, 2003).

Two sites deserve special mention for geoarchaeology. At Grotte du Prince, MIS 7 marine deposits are preserved, overlain by MIS 6 (“Riss”) bone-bearing cryoclastic breccias from which Acheulian tools and a *Homo* sp. iliac bone were recovered. Riparo Mochi, a rock shelter, has become a southern European reference for the so-called Middle-to-Upper Paleolithic (MP-UP) transition, thanks to recent radiocarbon determinations on marine shell beads suggesting an earlier UP start than previously thought – 43–42 ka cal BC (Douka et al., 2012). Flint and jasper come from distances of 40–200 km, greatly exceeding the MP ranges. Also steatite, used to carve female figurines during the Gravettian tradition (30–18 ka cal BP), was obtained through faraway contacts (Mussi, 1991). Together with 18 UP burials from the extensive excavations of 1860–1905, these “Venuses” gave the Grimaldi caves great fame and made these caves an important place in the history of Paleolithic research.



Grimaldi Caves, Figure 1 A plan of the Grimaldi caves and associated open-air Paleolithic sites.

Francesco G. Fedele retired

Bibliography

Douka, K., Grimaldi, S., Boschian, G., del Lucchese, A., and Higham, T. F. G., 2012. A new chronostratigraphic framework for the Upper Palaeolithic of Riparo Mochi (Italy). *Journal of Human Evolution*, **62**(2), 286–299.

Furlani, S., Pappalardo, M., Gómez-Pujol, L., and Chelli, A., 2014. The rock coast of the Mediterranean and Black seas. In Kennedy, D. M., Stephenson, W. J., and Naylor, L. A. (eds.), *Rock Coast Geomorphology: A Global Synthesis*. London: The Geological Society. Geological Society of London Memoir, Vol. 40, pp. 89–123.

Mussi, M., 1991. L'utilisation de la stéatite dans les grottes des Balzi Rossi (ou grottes de Grimaldi). *Gallia Préhistoire*, **33**(33), 1–16.

Stiner, M. C., 2003. 'Standardization' in Upper Paleolithic ornaments at the coastal sites of Riparo Mochi and Üçağızlı Cave. In Zilhão, J., and d'Errico, F. (eds.), *The Chronology of the Aurignacian and of the Transitional Technocomplexes: Dating, Stratigraphies, Cultural Implications*. Lisbon: Instituto Português de Arqueologia. Trabalhos de Arqueologia 33, pp. 49–59.

GROUND-PENETRATING RADAR

Lawrence B. Conyers
Department of Anthropology, University of Denver, Denver, CO, USA

Synonyms

Georadar; Ground-probing radar

Definitions

Amplitude: The intensity or strength of a recorded electromagnetic wave.

Attenuation: The dissipation of electromagnetic energy due to the spreading of energy in the ground and the conductivity of earth materials.

Noise: Any recorded energy from a source that is not the object of study.

Point target: A spatially restricted object in the ground that usually produces a hyperbolic-shaped reflection.

Pulse: A very short duration electrical charge placed on an antenna in order to produce an electromagnetic wave that propagates outward.

Range-gain: A data processing step that increases the amplitudes of waves recorded in the ground so that they are visible in two-dimensional reflection profiles.

Reflection hyperbola: The reflection produced by a buried point source.

Stacking: The averaging of recorded waves in sequential traces to produce one composite trace as a way to even out surface disturbances, ground clutter, or noise.

Time window: The two-way travel time within which radar waves are recorded, measured in nanoseconds (ns).

Trace: A series of waves recorded at one spot on the ground surface.

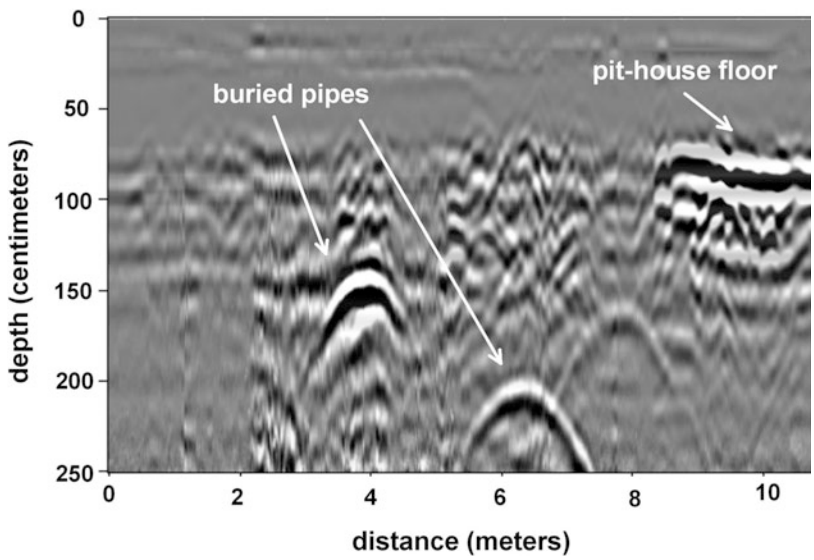
Introduction

Ground-penetrating radar is a near-surface geophysical technique that is employed in order to discover and map buried archaeological features and associated geological units in ways not possible using traditional excavation field methods. It is the best near-surface geophysical method that characterizes the three-dimensional arrangement of subsurface geological units and associated archaeological features. The method consists of measuring the elapsed time between the emission of pulses of electromagnetic (radar) energy (generated at the ground surface by an antenna), transmitted to some depth as propagating waves, reflected off buried discontinuities, and then received back at the surface by a receiving antenna. The distribution and orientation of such subsurface reflections of geological or archaeological importance are then identified and mapped. When aspects of those radar reflections are related to buried features of archaeological sites – such as the presence of architecture, living surfaces, use areas, or other associated cultural features – high-definition three-dimensional maps and images of buried sites can be produced. Ground-penetrating radar is a geophysical technique that is most effective at buried sites where artifacts and features of interest are located between 20 cm and 4 m beneath the surface, but it has occasionally been used for more deeply buried deposits.

Ground-penetrating radar data are acquired by radar waves reflecting off buried objects, features, or bedding contacts in the ground and then detected back at a receiving antenna (Figure 1). Antennas are usually moved along transects, and hundreds or even thousands of reflections are recorded every meter. Distance along transects is commonly measured by an attached survey wheel, as reflections are digitized and saved on a computer. As radar pulses are being transmitted through various materials on their way to the buried target features, their velocity will change depending on the physical and chemical properties of the material through which they are traveling (Conyers, 2013, 107). Each distinct velocity change at an interface of differing materials generates a reflected wave, which travels back to the surface. When the velocity of radar energy in the ground is calculated, travel times of the reflected waves can be converted to depth within the ground (Conyers, 2013, 28), producing a three-dimensional dataset.

Most typically in archaeological GPR, surface radar antennas are moved along the ground in linear transects, and two-dimensional profiles of a large number of reflections at various depths are created, producing profiles of subsurface stratigraphy and buried archaeological features along parallel and sometimes perpendicular lines like long cross sections through the ground (Figure 2). However, depending on surface complexity and vegetation cover, reflection profiles can be oriented in any direction and length in order to answer a variety of geological and archaeological questions. When data are acquired in a closely spaced series of

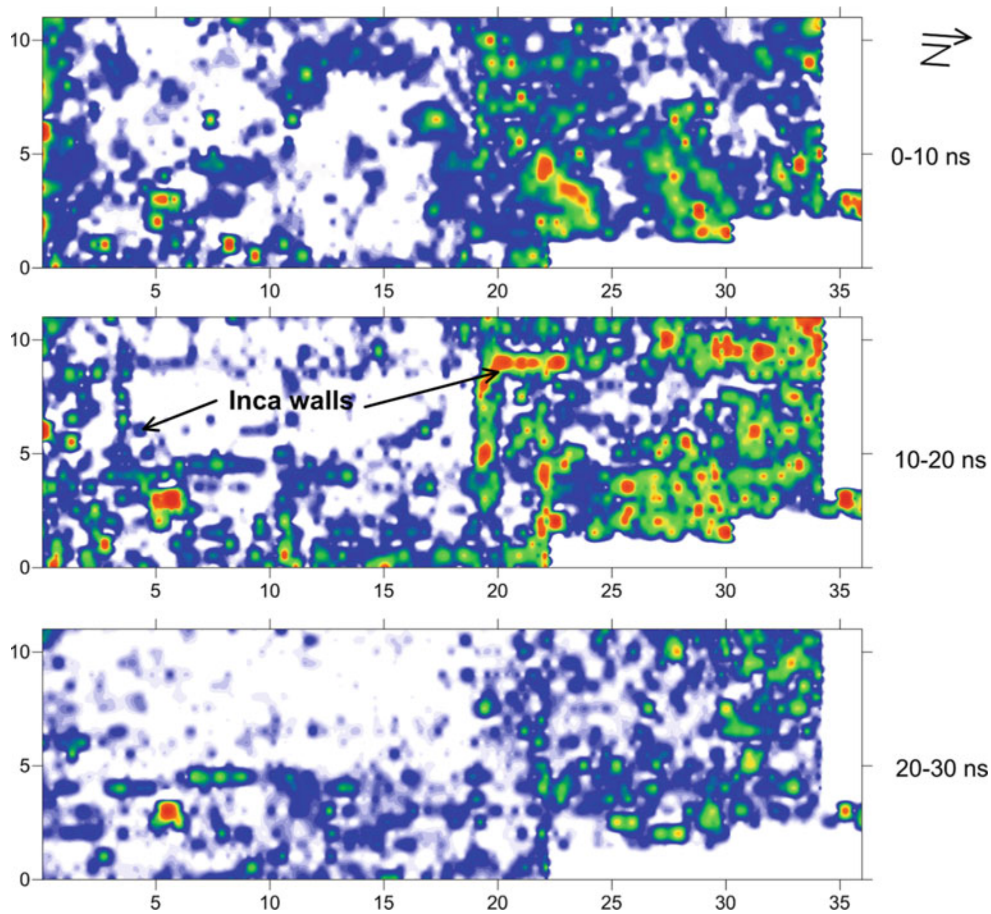
Ground-Penetrating Radar, Figure 1 GPR equipment including 400 MHz transmission and reception antennas in the fiberglass box, attached survey wheel for distance measurement, and the radar control unit and computer attached to the operator's back. This is a Geophysical Survey Systems SIR-3000 system.



Ground-Penetrating Radar, Figure 2 A reflection profile 11 m long displaying reflections to a depth of 250 cm. Two hyperbolic reflections from buried pipes are point source reflections, and a distinct planar reflection was produced from a buried house floor. This profile was collected in a water pipeline right-of-way near Alamogordo, New Mexico, USA.

transects within a grid, and reflections are correlated across transects and processed, three-dimensional maps and other images of buried features and associated stratigraphy can be constructed (Conyers, 2012, 25; Conyers, 2013, 69; see also Conyers, 2015). These images and maps are produced with the aid of computer software that can create maps using many thousands of reflection amplitudes from all profiles within a grid at various depths (Figure 3).

Ground-penetrating radar surveys allow for a relatively wide coverage of surface area in a short period of time, with grids of 50 × 50 m composed of as many as 100 profiles collected in a few hours. Often, the GPR method is used for detailed three-dimensional analysis of smaller grids within more extensively surveyed areas that are mapped using other geophysical methods, such as magnetometry and earth resistance that can be used later to produce scaled two-dimensional maps.



Ground-Penetrating Radar, Figure 3 Amplitude slice-maps displayed in two-way radar travel time measured in nanoseconds (ns). Each 10 ns interval represents approximately 40 cm of depth. The horizontal slice representing 10–20 ns shows distinct high-amplitude walls, produced from buried Inca structures in highland Ecuador.

Ground condition variables

The success of GPR surveys is to a great extent dependent on soil and sediment mineralogy, clay content, ground moisture, depth of burial, surface topography, and vegetation (Conyers, 2013, 24). Radar wave penetration, and the ability to transmit energy through the ground and reflect energy back to the surface, is often enhanced in a dry environment, but dry ground is not necessarily a prerequisite. Some GPR surveys have been quite successful even in very wet environments as long as the medium through which the radar energy passes is not electrically conductive (Conyers, 2004). The mineralogy of materials in the ground is also important, especially clay type and content. Sediments that contain electrically resistive clay minerals such as kaolinite are excellent at allowing the transmission of radar waves, while bentonite, montmorillonite, and other electrically conductive clays are generally poor. Fresh water is an excellent medium for GPR, so radar energy transmission and energy can travel to great depths in lakes and through glacial ice. But when water comes in contact with electrically conductive minerals, an attenuating environment is created that destroys radar energy rapidly, conducting away the transmitted energy. Salty or brackish water will not allow radar energy transmission, and therefore, the method cannot be used in environments of this sort.

Transmission, reflection, and recording of radar waves

The transmission of high frequency radar waves into the earth begins at the surface, with waves moving at the speed of light, then decreasing in velocity as they propagate into the ground. The elapsed time between transmission, reflection off buried discontinuities, and reception back at a surface radar antenna is then measured. Radar energy is generated at a transmitting antenna that is placed on, or near, the ground surface, and waves are generated which propagate downward into the ground where some of those waves are refracted at some interfaces and others reflected back to the surface. The discontinuities where reflections occur are usually created by changes in electrical properties of the sediment or soil, lithologic changes, differences in bulk density at stratigraphic interfaces, and, most importantly, water content variations, which are affected by all these variables (Conyers, 2012, 37; Conyers, 2013, 26). Any change in the velocity of propagating radar waves caused by changes in these ground conditions will generate a reflection. High-amplitude reflected waves are therefore often generated at the interfaces of archaeological features and the surrounding soil or sediment and at the contacts between geological units that vary in composition, density, and porosity, all of which affect the water saturation and therefore the velocity of transmitted radar energy. Void spaces, which may be encountered in burials, tombs, or tunnels, will also generate significant radar reflections due to a significant change in radar wave velocity, as propagating energy increases back to the speed of light in air.

The depth to which radar energy can penetrate and the amount of definition that can be expected from reflections generated at buried surfaces is partially controlled by the frequency of the radar energy transmitted. Radar energy frequency is dependent on the type of antenna used, as the antenna controls both the wavelength of the propagating wave and the amount of attenuation of the waves in the ground. Standard GPR antennas used in geoarchaeology propagate radar energy that varies in bandwidth between 10 and 1,200 megahertz (MHz). Antennas usually come in standard frequencies, with each antenna having one center frequency, but actually producing radar energy that ranges around that center by about one octave (one half and two times the center frequency). In general, low-frequency waves can propagate deeper into the ground, but they yield less subsurface resolution. For instance, 200 MHz antennas can potentially transmit energy to 4 or 5 m depth, but they are capable of resolving features or stratigraphy of only about a meter or so in dimension or thickness. In contrast, a 900 MHz antenna can resolve features as small as a few centimeters, but it is capable of energy transmission to only about a meter under most ground conditions. In electrically conductive ground, all radar energy is usually attenuated at very shallow depths, no matter what its frequency.

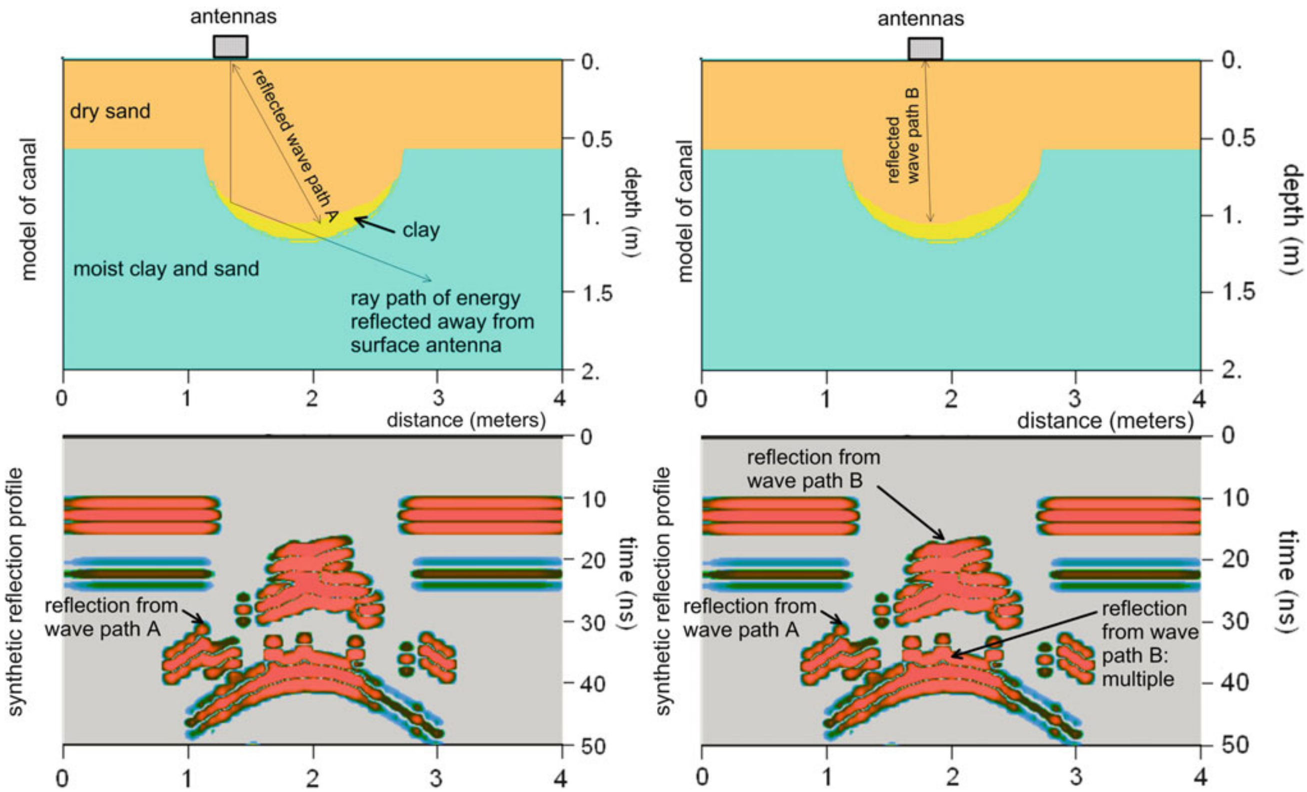
The two-way travel time, amplitude, and wavelength of the reflected radar waves produced by buried interfaces are recorded at the surface antennas, amplified, processed, and recorded for immediate viewing and later post-acquisition processing and display. Many reflections are recorded from various depths in the ground, with one series of waves at one location termed a reflection trace. Reflections are recorded within preset time windows, measured in nanoseconds of two-way travel time. During usual data acquisition procedures, two-dimensional profiles are created as the radar pulse transmission, reflection, and recording process is repeated many times a second and at programmed distances along transects as the antennas are pulled along the ground surface. Individual traces are then collected and placed in sequential order to produce profiles that represent vertical "slices" through the ground (Figure 2). Distance along each line is recorded for accurate placement of all reflection traces within a surveyed grid; this can be done using a survey wheel, GPS, or manual distance marks ticked off along tape measures.

Radar energy becomes both dispersed and attenuated as waves move into the ground after emerging from surface antennas. Energy that is reflected back toward the surface then will suffer additional attenuation by the material through which it passes, before finally being recorded at the surface. Therefore, to be detected as reflections, important subsurface interfaces must not only have sufficient electrical contrast at their boundary but also must be located at a shallow enough depth where sufficient radar energy is still available for reflection. As radar energy is propagated to increasing depths, the signal becomes weaker as it spreads out over a greater volume of the subsurface and is absorbed by the ground, making less energy available for reflection. For every site, the maximum depth of penetration will vary with the geological conditions and the equipment being used. Post-acquisition data filtering and other data amplification techniques (termed range-gaining) can sometimes be applied to reflection data after acquisition that will enhance some very low-amplitude reflections in order to make them more visible.

Other variables affecting GPR

Radar waves transmitted from standard commercial antennas radiate energy into the ground in an elliptical cone with the apex of the cone at the center of the transmitting antenna (Conyers, 2013, 67). This elliptical cone of transmission forms because the electrical field produced by the antenna is generated parallel to its long axis and therefore usually radiates into the ground perpendicular to the direction of antenna movement along the ground surface. The radiation pattern is generated from a horizontal electric dipole to which elements called shields are sometimes added that effectively reduce upward radiation. Some antennas, especially those in the low-frequency range from 10 to 200 MHz or so, are often not well shielded, or not shielded at all, and will therefore radiate radar energy in all directions. Lower frequency antennas also transmit energy that spreads out more as it leaves the antenna and moves into the ground. Unshielded antennas can generate reflections from a nearby person pulling the radar antenna, or from any other objects nearby, such as trees or buildings. Discrimination of individual buried features can then become more difficult, but anomalous reflections can sometimes be filtered out later during data processing.

Radar energy that is reflected off a buried subsurface interface that slopes away from a surface transmitting antenna will be reflected away from the receiving antenna and will not be recorded (Figure 4). A buried surface of this sort would be visible only if additional traverses were

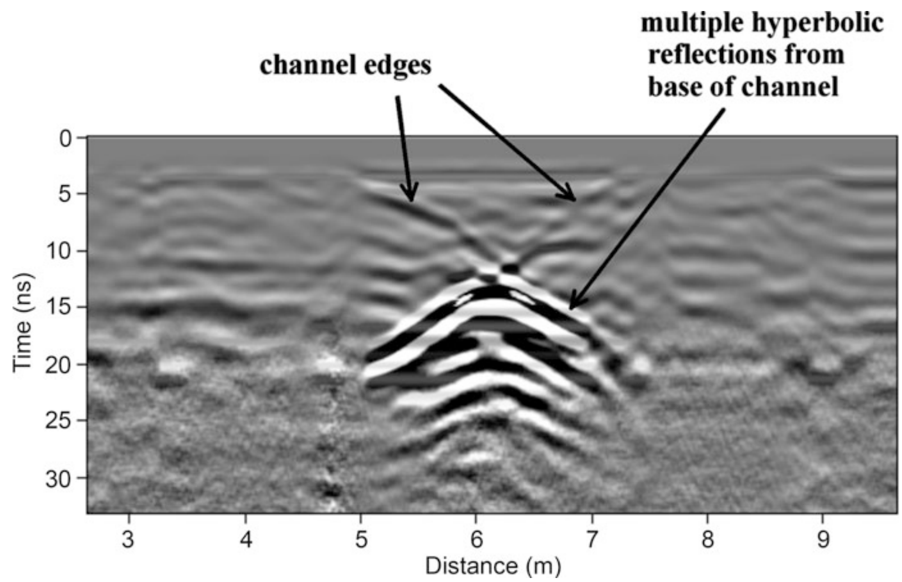


Ground-Penetrating Radar, Figure 4 Computer-generated reflection model of a buried canal filled with a thin layer of clay illustrating how complex reflections can be recorded as energy is transmitted through the ground. On either side of the trench, the reflections are accurately recorded from the interface of the dry sand and the underlying moist clay and sand layer. However, when the antennas are over the trench but not over its center (*left side*), radar waves transmitted directly down intersect the clay layer and reflect away from the surface antenna, so their direct return is not recorded. Energy also is transmitted in front (and behind) the antennas, and thus, the waves that emerge from the antenna and move along path A are recorded as if they were reflected below the canal due to their longer travel times. As the antennas are moved forward and into the center of the canal, the actual location of the bottom of the canal reflection is recorded correctly from energy moving along path B. The same cycle and recording are repeated many thousands of times, creating this complex series of reflections in the synthetic reflection profile. Only the channel's base is recorded correctly in space with the other interface indications created by reflections that travel along other, longer wave paths.

collected at an orientation that would allow reflected energy to travel back to the surface recording antenna. For this reason, it is always important to acquire lines of reflection data within a closely spaced surface grid and sometimes in transects perpendicular to each other.

Small buried objects that reflect radar energy are termed point targets (Figure 2), while broader more extensive units such as stratigraphic and soil horizons or large, flat archaeological features such as floors are termed planar targets. Point targets can be walls, tunnels, voids, artifacts, or other nonplanar objects that often possess little of their own surface area with which to reflect radar energy. If they are too small, they will be totally invisible if lower frequency energy is transmitted into the ground. However, if high frequency energy is transmitted, many reflections will be generated from many small point targets, and this potentially crowded return of reflections can be described as clutter, if they are not the targets of the survey. In all cases, buried features need to be larger than the clutter to be visible, and they are generally not visible unless they are larger than about 40 % of the wavelength of the propagating energy (Conyers, 2013, 72).

Point source reflections often occur in the shape of hyperbolas (Figures 2 and 5). This reflection shape is produced because, as described above, most GPR antennas produce a transmitted radar beam that propagates downward from the surface in a conical pattern, radiating outward as energy travels to depth. Radar waves will therefore be reflected from buried point sources that are not located directly below the transmitting antenna but are still within the "beam" of propagating waves. The travel paths of oblique radar waves to and from the ground surface to point sources in front and back of the antenna are longer (as measured in radar travel time), but the reflections generated are recorded as if they were directly below but just deeper in the ground. As the surface



Ground-Penetrating Radar, Figure 5 Reflection profile from a buried channel that demonstrates reflections similar to those modeled in Figure 4. The channel edges are very low amplitude, while a very high-amplitude series of hyperbolic reflections are recorded from the base of the channel, which are recorded as high amplitude due to the upwardly convex surface that focuses energy. This profile was collected over an early agricultural age canal near Tucson, Arizona, USA.

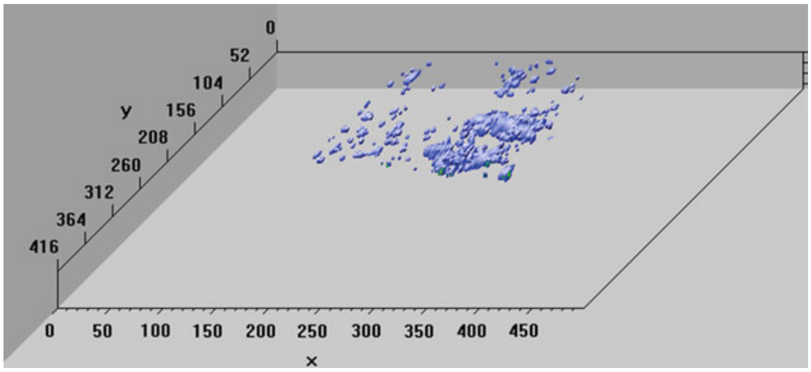
antenna moves closer to a buried point source, the receiving antenna will continue to record reflections from the buried point source prior to arriving directly on top of it and continue to record reflections from it moving away. A reflection hyperbola is then generated with only the apex of the reflection denoting the actual location of the object in the ground, with the arms of the hyperbola creating a record of reflections that traveled the increasingly oblique wave paths. In some cases, only half of a hyperbola may be recorded, if just the corner or edge of a planar feature is causing a discrete reflection, such as the edge of a buried house floor or platform. The shape of such hyperbolas can also be used to calculate radar travel velocity in the ground since their shape is a function of the velocity of radar energy as it moves in the ground (Conyers, 2013, 113). Hyperbola analysis to obtain velocities is therefore an extremely efficient and accurate way to convert radar travel times to depth in the ground.

Radar waves travel through the ground in complex ways, spreading out with depth, refracting, reflecting, and attenuating, as energy encounters differing materials in various orientations. This can sometimes lead to the recording of reflections that have not always traveled directly from the surface antenna to some buried reflection surface and back to the antenna. Radar energy can often reflect multiple times from various layers or even from the ground surface or the antenna itself, leading to reflections that are not indicative of the buried features of interest. To minimize the amount of reflection data that are recorded from the sides of a two-dimensional transect, the long axes of the transmitting antennas are usually aligned perpendicular to the profile direction. However, if there are buried elongated features parallel to the direction of antenna travel (and therefore parallel to the electromagnetic field generated by the antenna), only a small portion of the radar energy will be reflected back to the surface, so these features are likely to remain invisible.

Most GPR antennas produce radar energy in frequencies lying within the same frequency spectrum as those used in television, FM radio, and portable communication devices, and therefore, background noise will also be recorded along with reflections that come from within the ground. This noise can sometimes be removed during data collection or during post-acquisition processing where some frequencies can be enhanced and others filtered out.

When antennas move over uneven ground and clumps of vegetation, transmitted radar energy couples with the ground in various ways and can move into the ground in various orientations, producing anomalous recorded amplitude reflections. For this reason, it is preferable to move antennas in transects lying as flat as possible and at the same distance from the ground, in order to reduce coupling change anomalies.

Reflection from a buried interface that contains ridges or troughs, or any other irregular features, can focus or scatter radar energy, depending on the surface's orientation and the location of the antennas on the ground surface. If a reflective surface is convex upward, energy will tend to be reflected away from the receiving antenna, and only a low-amplitude reflection will be recorded.



Ground-Penetrating Radar, Figure 6 Isosurface image of a buried pit house floor and associated rocks in a three-dimensional block of reflections. These reflections are from a pit house buried in sand dunes near Port Orford, Oregon, USA.

The opposite is true when the buried surface is concave upward, which will focus energy, and a very high-amplitude reflection will be recorded.

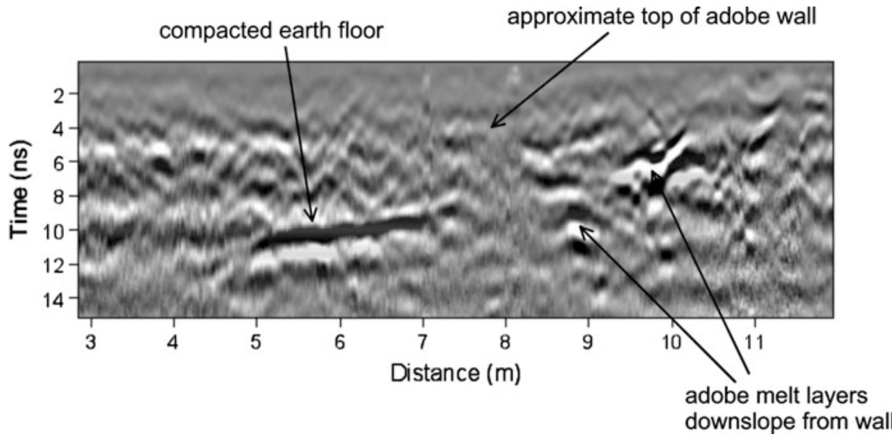
Reflection analysis and interpretation

Raw GPR reflection data comprise a collection of individual traces consisting of reflections recorded at different times within a recording time window. When two-dimensional profiles are collected, these traces are spaced at various distances along transects, which can be displayed as profiles. New systems are being developed that can send and receive multiple radar pulses within complex three-dimensional grids that can potentially produce very precise three-dimensional images, but these systems have not yet been perfected (Conyers and Leckebusch, 2010). Each reflection trace contains a series of waves that vary in amplitude depending on the amount and intensity of energy reflection that occurs at buried interfaces. When these traces are plotted sequentially in standard two-dimensional profiles, amplitudes created from buried interfaces often denote layers of importance, with the strength of the reflections indicating the differences in composition between buried materials.

Each profile can be interpreted individually, after which buried features of interest are often immediately visible. When many tens or hundreds of profiles are collected forming a grid, this method of interpretation can often be laborious, so it is efficient to use computer software to produce maps and other images of the relative amplitudes of reflections in slice-maps (Figure 2) or to produce three-dimensional isosurfaces (Figure 6). In these images, areas of low-amplitude reflected waves indicate little or no reflection and therefore uniform materials, while high-amplitude reflections denote buried interfaces between highly contrasting materials, which could be stratigraphic interfaces or buried archaeological features. Amplitude slices need not be constructed horizontally or even in equal time intervals. They can also vary in thickness and orientation, depending on the questions asked. Surface topographic variations and the subsurface orientation of features and stratigraphy of a site may necessitate the construction of slices that are neither uniform in thickness nor horizontal. To compute amplitude slices, computer software compares amplitude variations within traces that were recorded within a defined window, averages them over a defined search radius, and grids and displays the relative reflection amplitudes. Degrees of amplitude variation in each time-slice can be assigned arbitrary colors or shades of gray along a nominal scale in map view or placed in a three-dimensional block and assigned colors or patterns so that reflections are visible (Conyers et al., 2002; Leckebusch, 2003; Goodman et al., 2004; Conyers, 2013, 187). In isosurface images, computer-generated light sources that simulate rays of the sun can then be used to shade and shadow the rendered features in order to enhance them, and the features can be rotated and shaded until a desired image is produced.

Both high and low amplitudes can denote buried features of interest, and only an understanding of the nature of the geological or archaeological features in the test area will allow for accurate interpretations. Compacted floors will often retain moisture and produce distinct planar high-amplitude reflections (Figure 7), while adjacent earthen walls of homogeneous material will remain invisible because there are no buried surfaces to reflect energy. The vertical contact between the wall and the adjacent material will also not reflect waves because transmitted radar energy passes by that interface at too low an angle without producing any reflections. Other stratigraphic features adjacent to the otherwise invisible walls might be visible, but they could be difficult to interpret without knowing something of the buried architectural context or understanding the types and composition of archaeological or geological features common in the area.

Amplitude slice-maps in areas of earthen architecture must be evaluated by locating areas showing no reflections, which denote the location of important features (Figure 8). This demonstrates how important it is to define whether the features of interest are highly reflective or



Ground-Penetrating Radar, Figure 7 Reflection profile shows a distinct high-amplitude reflection from a compacted earth floor, with an associated vertical adobe wall which does not reflect radar energy. The wall is effectively invisible because it is composed of homogenous clay and sand, which contains no stratigraphic interfaces to reflect energy. The wall edges also do not reflect energy, as they are vertical and do not provide an interface that can reflect waves transmitted from the surface antenna. This profile was collected over Hohokam architecture in Tucson, Arizona, USA.

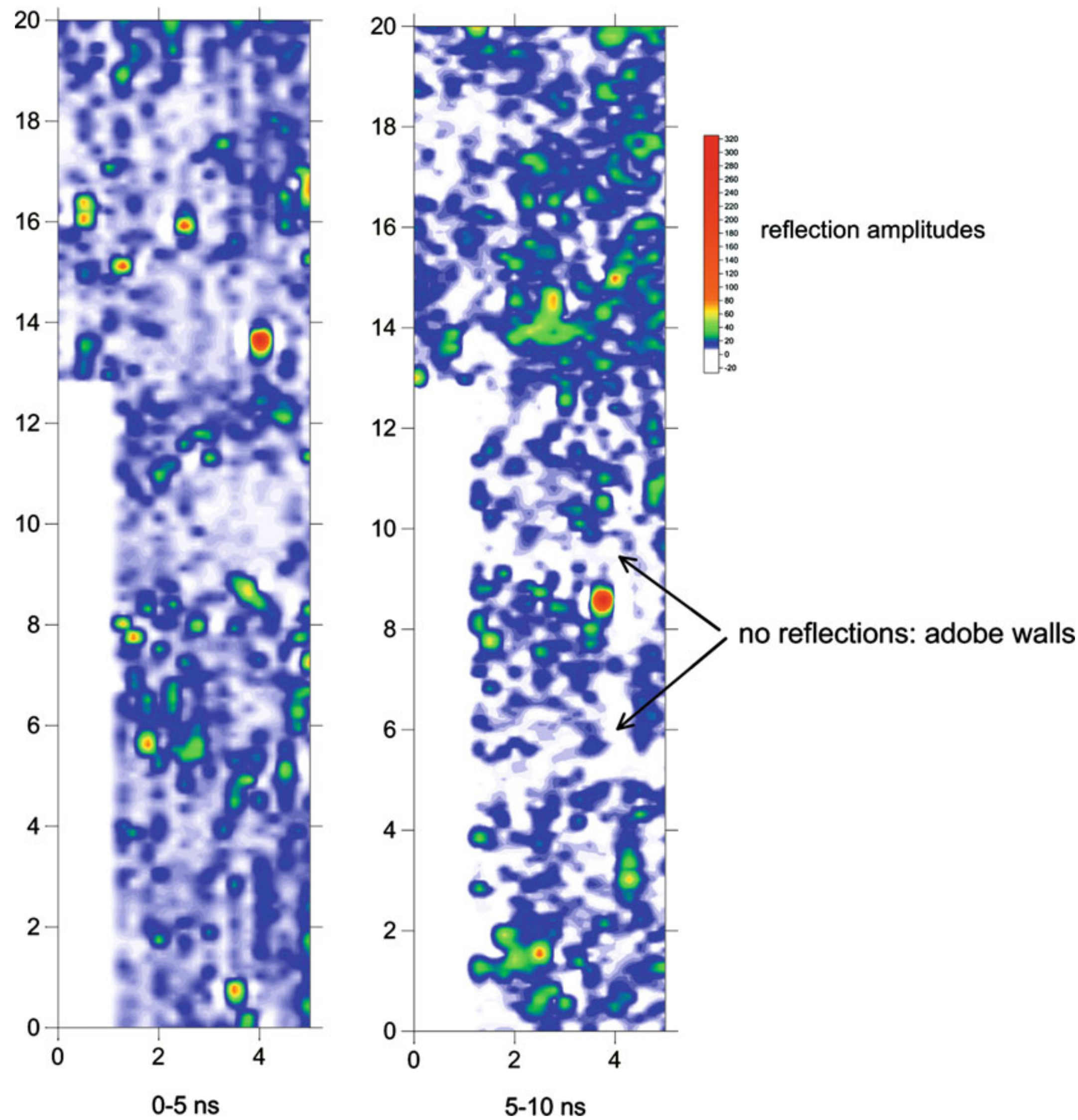
perhaps not reflective at all. There has always been a bias in GPR toward analyzing and mapping only the strongest reflections recorded; however, low- or no-amplitude areas may also be important, depending on the type of materials buried in the ground.

Various computer programs are available that use different algorithms for producing amplitude maps, all of which can be modified by the user depending on the types of questions being asked. Some programs tend to average reflections, producing more general maps, while others produce images of almost every reflection in the ground, which tend to be more exact but also highly complex. Other programs were developed for certain commercial applications, such as pipe location or other geotechnical uses, and are less useful for archaeological feature mapping and identification (Figure 9).

Using GPR for archaeological interpretation

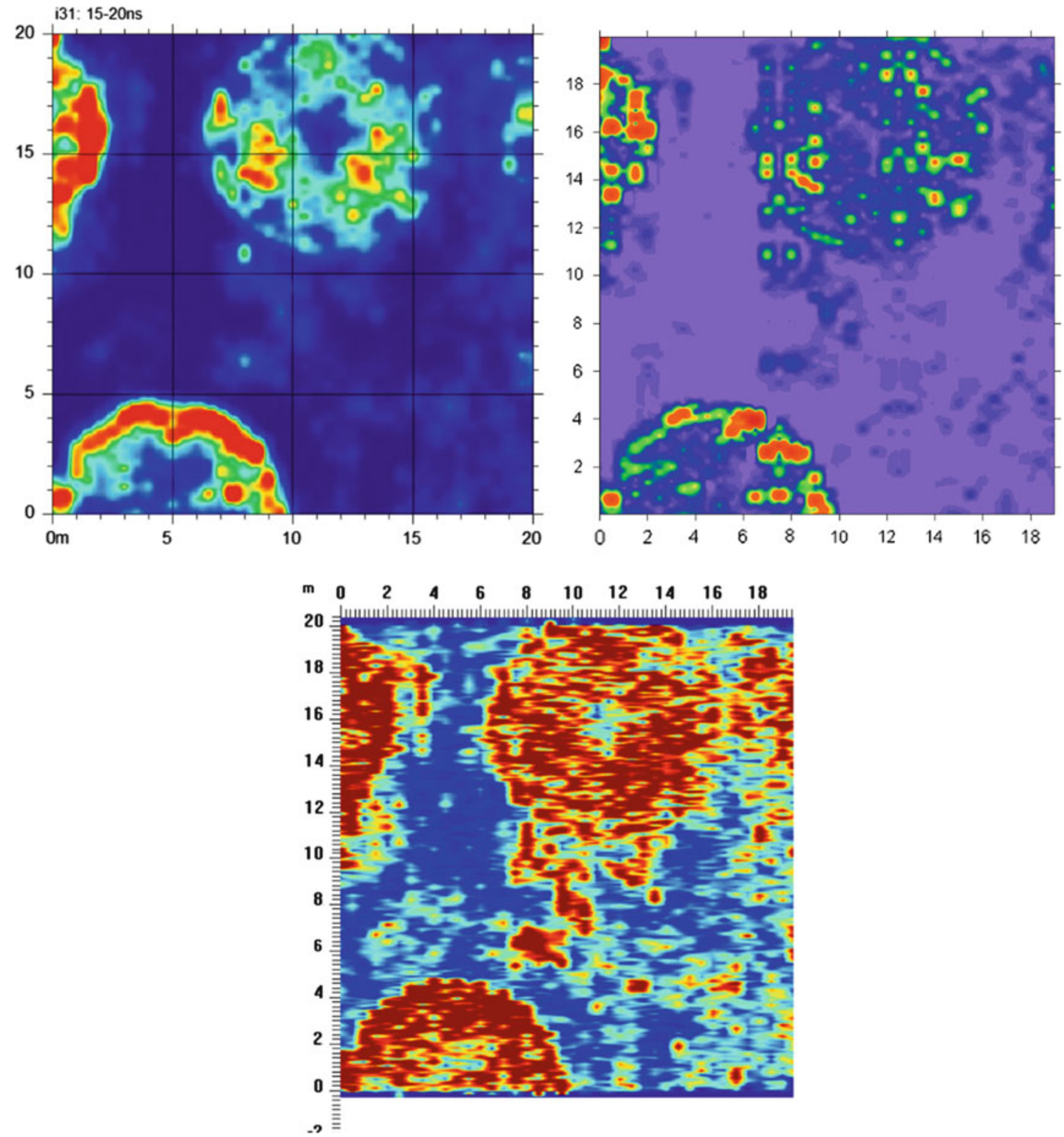
Archaeological geophysics has historically been used as a method for discovering buried archaeological remains and less often as a dataset for interpreting aspects of human history and testing anthropological hypotheses relating to culture. However, GPR, with its three-dimensional mapping ability, can, and should, be used to test ideas about humans in ways that are similar to standard archaeological methods (Conyers, 2010; Conyers and Leckebusch, 2010). If architecture, site organization, or any other aspects of human construction or modification of the buried landscape can be indicative of behavior, then GPR mapping can be of great benefit (Conyers, 2009). The GPR method can be an especially powerful tool when combined with standard archaeological excavations, especially when the geophysical images are used as a guide to the placement of subsurface tests. In this way, limited excavation and the exposure and study of important archaeological features and associated geological layers can be made, and information about those buried features can be projected in three-dimensions over a wide area.

An example of this type of GPR analysis is the testing of extensive surface features in southeastern Utah, USA, where a number of circular depressions were visible on the surface associated with scattered pottery that suggested there might be great kivas below. During the interval when the pottery recovered at the surface was made (about AD 900–1150), this general area in the southwestern USA was dominated by one political and economic entity centered about 200 km away at Chaco Canyon, New Mexico (Conyers and Osburn, 2006; Conyers, 2010; Conyers, 2012, 183). At Chaco Canyon and elsewhere in the American Southwest, great kivas of this age were architectural structures used to indicate strong political and economic ties to Chaco. In order to test the hypothesis that the area of presumed great kivas in Utah was connected in some way with Chaco Canyon, GPR data were collected on five of the large surface depressions. GPR maps at sites 1 through 3 (Figure 10) showed that there were kivas buried below the surface; they were not “great” kivas, however, but instead small, circular kiva structures consistent with a low population density farming community that was perhaps aware of Chaco Canyon, but not connected in the ways that had been hypothesized. Two of the sites tested with GPR contained no architecture whatever and are likely remnants of modern water reservoirs. In this case, GPR was the only method, barring extensive excavations, that could have discovered and mapped the presence and function of these buried architectural remains.



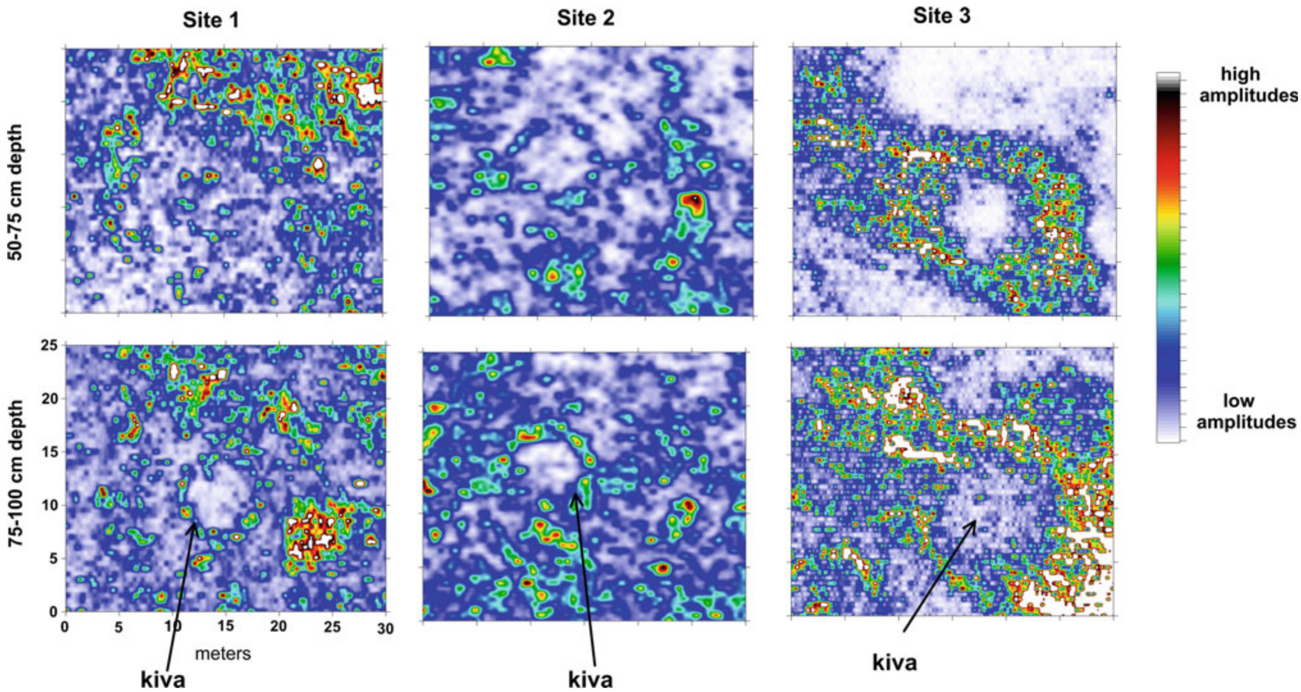
Ground-Penetrating Radar, Figure 8 Amplitude slice-map of the adobe walls shown in Figure 7. The walls are shown in white as areas of no reflection, while random stones or layers of adobe melt adjacent to the walls produce high-amplitude reflections. These are Hohokam walls in Tucson, Arizona, USA.

In the Middle East, much is known about the late Nabataeans, desert traders who constructed monumental architecture in the vicinity of Petra, Jordan, and other areas along trade routes between Arabia and the Mediterranean coast (Conyers, 2010; Conyers, 2012, 187). In an attempt to understand the habitation of the Petra area prior to the construction of monumental architecture beginning in the first few centuries BC, GPR data were collected in an area called the Lower Market (Conyers et al., 2002). While the near-surface remains were easily mapped with GPR (Figure 11a), the deeper reflections were more complex and necessitated buried topographic adjustment to sloping stratigraphy. It was apparent by studying the reflection profiles that this area had been at one time on the edge of a wadi (small valley), which had been artificially filled and leveled prior to construction of temples and other structures in late Nabataean time. All GPR profiles were then interpreted to find the reflection corresponding to the buried living surface prior to filling, and amplitudes were mapped on that surface alone (Figure 11b, c). Those mapped reflection features showed that simple structures had been built bounding pathways leading to the valley bottom along with remains of other buildings along the upper edge of the valley; these

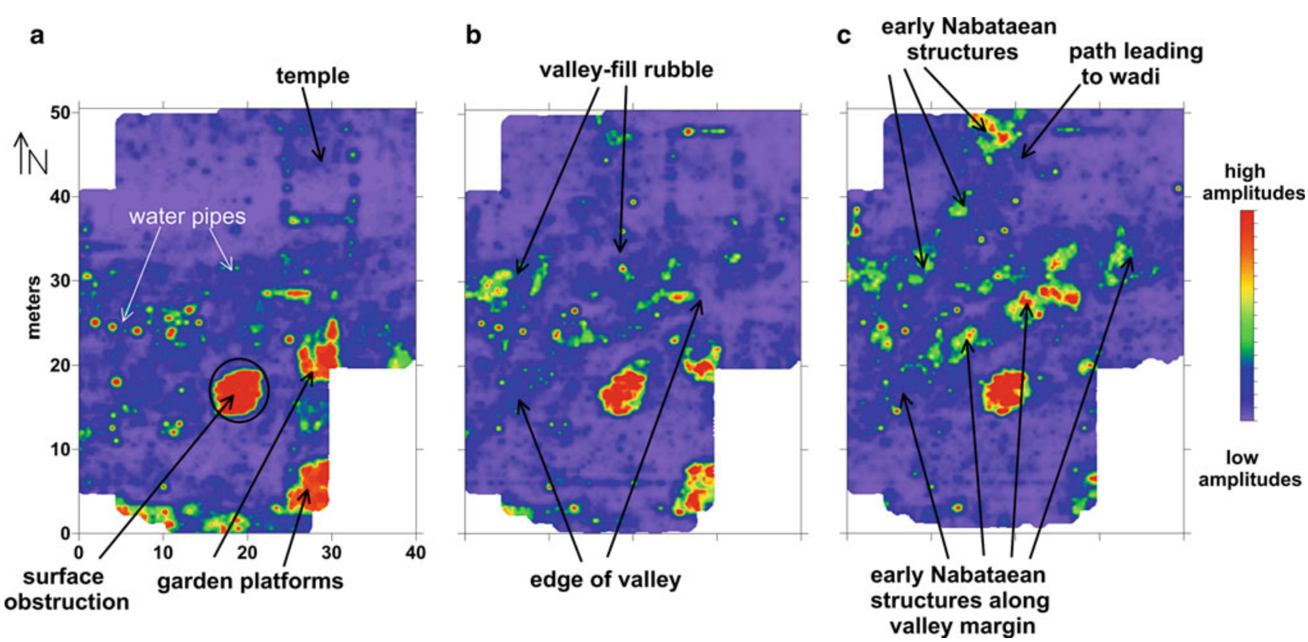


Ground-Penetrating Radar, Figure 9 Amplitude slice-maps of one layer from 15 to 20 ns constructed using three different software programs. Each uses different resampling and gridding algorithms, which create very different images of the same features. At this site, in Ohio, USA, there are three buried kiln floors. On the left is an averaged horizontal slice showing the general features, in the middle a very exact slice showing every reflection, and on the right a slice produced by a program used to map mostly buried pipes and other linear features.

structures were then covered during the filling and leveling process. Excavations along the north edge of the GPR grid confirmed that those structures were of early Nabataean age, a time when the valley was in the early stages of habitation by people who would later become the famous builders and wealthy traders of Petra. The GPR mapping showed that the ancestors of the Nabataeans of Petra lived in simple structures aligned with the natural topographic features of the valley and that these structures were later abandoned as the wealth from control of trade with Arabia increased and the site became commercially connected to the complex cultures of the Mediterranean (Conyers, 2010). Only the three-dimensional mapping capabilities of GPR that produced accurate images of this stratigraphically complex site could have yielded this interpretation of the early history of Petra without laborious and expensive excavation.



Ground-Penetrating Radar, Figure 10 Amplitude slice-maps of three sites in southeastern Utah, USA, illustrating high-amplitude circular kiva walls and other associated features. The interiors of these structures are filled with homogeneous wind-blown sand, which is non-reflective. At site 3, the kiva was constructed into bedrock, and therefore, both slices also display high-amplitude reflections from bedrock features.



Ground-Penetrating Radar, Figure 11 Amplitude slice-maps need not be horizontal but can be constructed to follow stratigraphic horizons which are not level with the ground surface. Map (**a**) shows architectural features in a horizontal slice between 50 and 100 cm of the surface. Maps (**b**) and (**c**) are subhorizontal slices and display features built on an ancient living surface, which slopes to the north. These are early Nabataean in age, from Petra, Jordan.

Conclusions

Ground-penetrating radar has the unique ability among near-surface geophysical methods to produce three-dimensional maps and images of buried architecture and other associated cultural and geological features. It can be used in any type of ground as long as the sediments and soils are not highly electrically conductive. Using high-definition two-dimensional reflection profiles produced along transects, three-dimensional maps of amplitude changes can be assembled that define physical and chemical changes in the ground that are related to archaeological and geological materials of importance. Interpretations that use individual two-dimensional reflection profiles combined into images of grids containing many tens or hundreds of profiles can be used to help understand buried archaeological sites, especially those that are geologically complex. When these data and maps are used to test ideas about human adaptation to ancient landscapes, they offer a powerful and time-effective way to study ancient human behavior, social organization, and other important archaeological and historical concepts.

In the processing of GPR reflection data for purposes of landscape analysis, maps and images must be generated and integrated with information obtained from other archaeological and geological data in order to provide age and context for the mapped sites. This can be done by inserting cultural data derived from excavations within amplitude maps that use only certain amplitudes within a three-dimensional volume of radar reflections. In all cases, the results of these amplitude images must be differentiated from the surrounding geological layers. When these multiple datasets are interpreted archaeologically, they can serve as a powerful tool that can integrate archaeological sites into the overall geological context.

Bibliography

Conyers, L. B., 2004. Moisture and soil differences as related to the spatial accuracy of amplitude maps at two archaeological test sites. In Slob, E. C., Yarovoy, A. G., and Rhebergen, J. B. (eds.), *Proceedings of the Tenth International Conference on Ground Penetrating Radar, June 21–24, 2004, Delft University of Technology, Delft, The Netherlands*. Piscataway: IEEE, pp. 435–438.

Conyers, L. B., 2009. Ground-penetrating radar for landscape archaeology: method and applications. In Campana, S., and Piro, S. (eds.), *Seeing the Unseen: Geophysics and Landscape Archaeology*. Leiden: CRC Press/Balkema, pp. 245–255.

Conyers, L. B., 2010. Ground-penetrating radar for anthropological research. *Antiquity*, **84**(323), 175–184.

Conyers, L. B., 2012. *Interpreting Ground-Penetrating Radar for Archaeology*. Walnut Creek: Left Coast Press.

Conyers, L. B., 2013. *Ground-Penetrating Radar for Archaeology*, 3rd edn. Lanham: Altamira Press. Geophysical Methods for Archaeology, Vol. 4.

Conyers, L. B., 2015. *Ground-Penetrating Radar for Geoarchaeology*. Oxford: Wiley.

Conyers, L. B., and Leckebusch, J., 2010. Geophysical archaeology research agendas for the future: some ground-penetrating radar examples. *Archaeological Prospection*, **17**(2), 117–123.

Conyers, L. B., and Osburn, T., 2006. GPR mapping to test anthropological hypotheses: a study from Comb Wash, Utah, American Southwest. In Daniel, J. J. (ed.), *Proceedings of the 11th International Conference on Ground-Penetrating Radar, June 19–22, 2006, Ohio State University, Columbus, Ohio*. Piscataway: IEEE, pp. 1–8.

Conyers, L. B., Ernenwein, E. G., and Bedal, L.-A., 2002. Ground-penetrating radar discovery at Petra, Jordan. *Antiquity*, **76**(292), 339–340.

Goodman, D., Piro, S., Nishimura, Y., Patterson, H., and Gaffney, V., 2004. Discovery of a 1st century AD Roman amphitheatre and other structures at the Forum Novum by GPR. *Journal of Environmental and Engineering Geophysics*, **9**, 35–42.

Leckebusch, J., 2003. Ground-penetrating radar: a modern three-dimensional prospection method. *Archaeological Prospection*, **10**(4), 213–240.

H

HARPPA

Joseph Schuldenrein
Geoarchaeology Research Associates, Yonkers, NY, USA

Introduction

Together with Mohenjo-daro, Harappa is the signature site of the third millennium BC culture of South Asia known as the Indus Valley or Harappan Civilization (Kenoyer, 1998; Possehl, 2002). The site formed the epicenter of a state society contemporaneous with the Mesopotamian and Egyptian cultures to the west, and it featured analogous elements of complex urban organization, trade, and commerce. In contrast with these other "cradles of civilization," Harappan script, while pervasive across the area's cultural heartland (Pakistan and India), remains undeciphered. There is, however, a growing body of archaeological evidence for contact among these three state-based societies.

Geoarchaeology of Harappa and the Indus Valley

The site of Harappa is in north-central Pakistan (Figure 1). It consists of at least four major mounds, which are the product of the accumulation of cultural deposits documenting the site's evolution as a major urban center whose date range is 3300–1700 BC. As is the case with Near Eastern tells, the Harappan mound complex was built on a base of natural floodplain sediments that irregularly flooded the local trunk stream, the Ravi River. The Ravi is one of "the Five Rivers," a series of subjacent, southwest trending drainages along which smaller Harappan mound complexes emerged. These Upper Indus channel and terrace landscapes emerge from the foothills of the Himalayas. They converge in central Pakistan to form the Indus River proper.

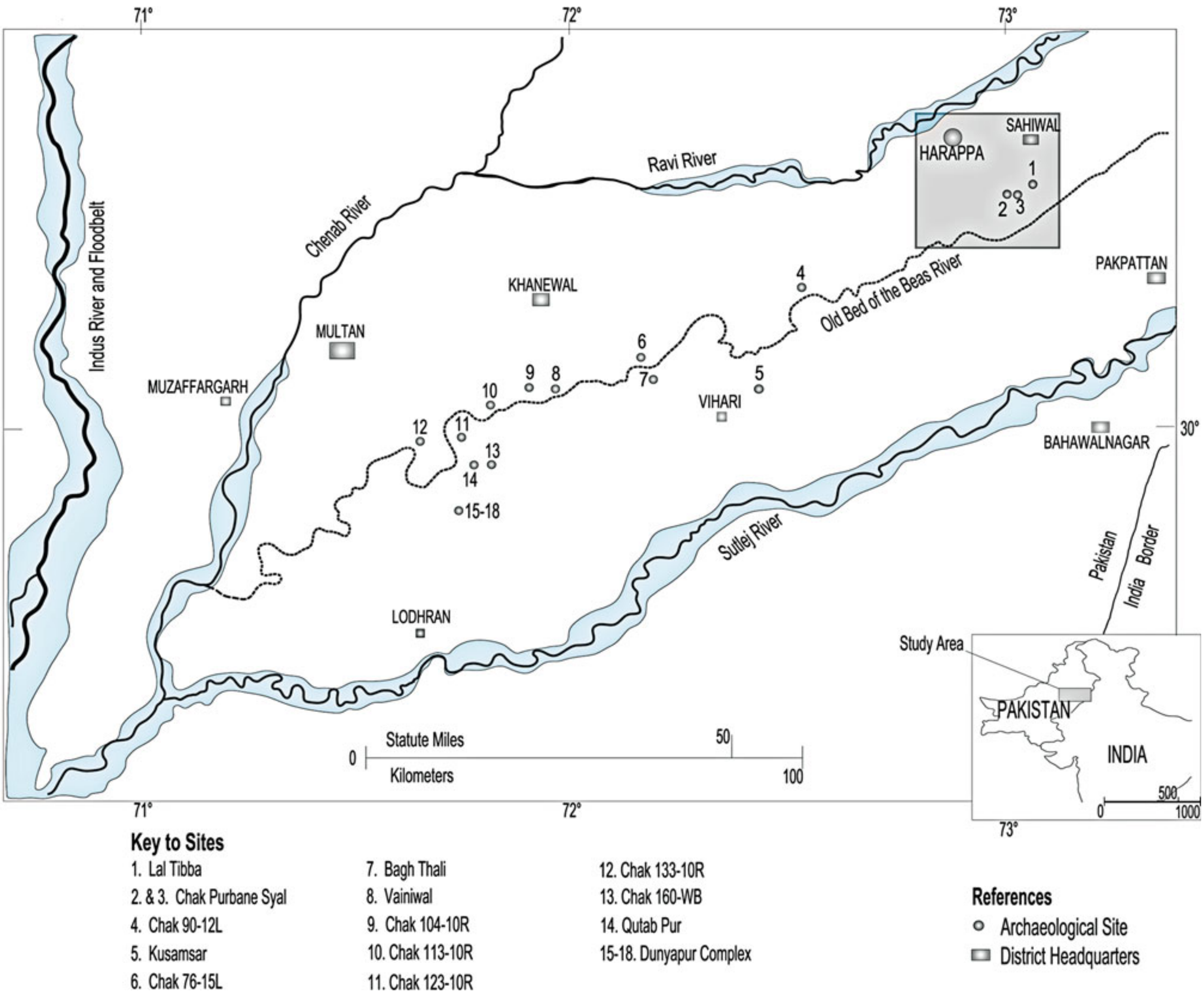
The 17 m high Harappan mound complex was recognized as early as 1834, and excavations date to the late nineteenth century, continuing into the twentieth century. Modern scientific archaeological research was initiated in the 1980s by combined US-based teams (chiefly Harvard, the University of Wisconsin, and New York University) and several European institutions. Work has been ongoing, intermittently, under the auspices of the Department of Archaeology and Museums, Government of Pakistan.

Baseline stratigraphic relations for the Harappa site were established by Wheeler (1947), who identified the base of the mound at an unconformity separating "natural" from "cultural" sediments. Two stratified units comprise the natural sediments; the uppermost is described as "alluvium" and the lower as "a dark brown earth" (Meadow et al., 1998). While over 100 radiocarbon dates have been processed to refine the 17 m high cultural stratigraphies, these pre-cultural horizons were only recently dated to the terminal Pleistocene. The unconformity marks an early Holocene interval of nondeposition (and probable cumulic soil development) at the site (Schuldenrein et al., 2004). Examination of the profile implicated longer-term stability of the upper alluvium. It represents a buried surface marking the top of a deeply weathered Pleistocene paleosol (ABk horizon) that graded into the lower "dark brown earth" (Bt1k-Bt2-Bt3y-C horizons).

More comprehensive mapping of the alluvial landscape incorporating and surrounding Harappa and its terraces centers on chronologically based, formal soil taxonomies. Within the non-cultural soils and sediments, antiquity is determined by degrees of clay translocation as well as carbonate redistributions and reprecipitation in the B horizon(s). Soil orders are entisols and alfisols, with the former representing late Holocene to historic weathering and the latter pre-dating 5000 BP (the period of cultural florescence) and extending to the terminal Pleistocene (Pendall and Amundson, 1990; Belcher and Belcher, 2000).

Smaller mounds and sites along the "Five Rivers" have been investigated geoarchaeologically over the past 30 years, and similar studies have been undertaken in southern Pakistan, along the Lower Indus (linked to the Mohenjo-daro

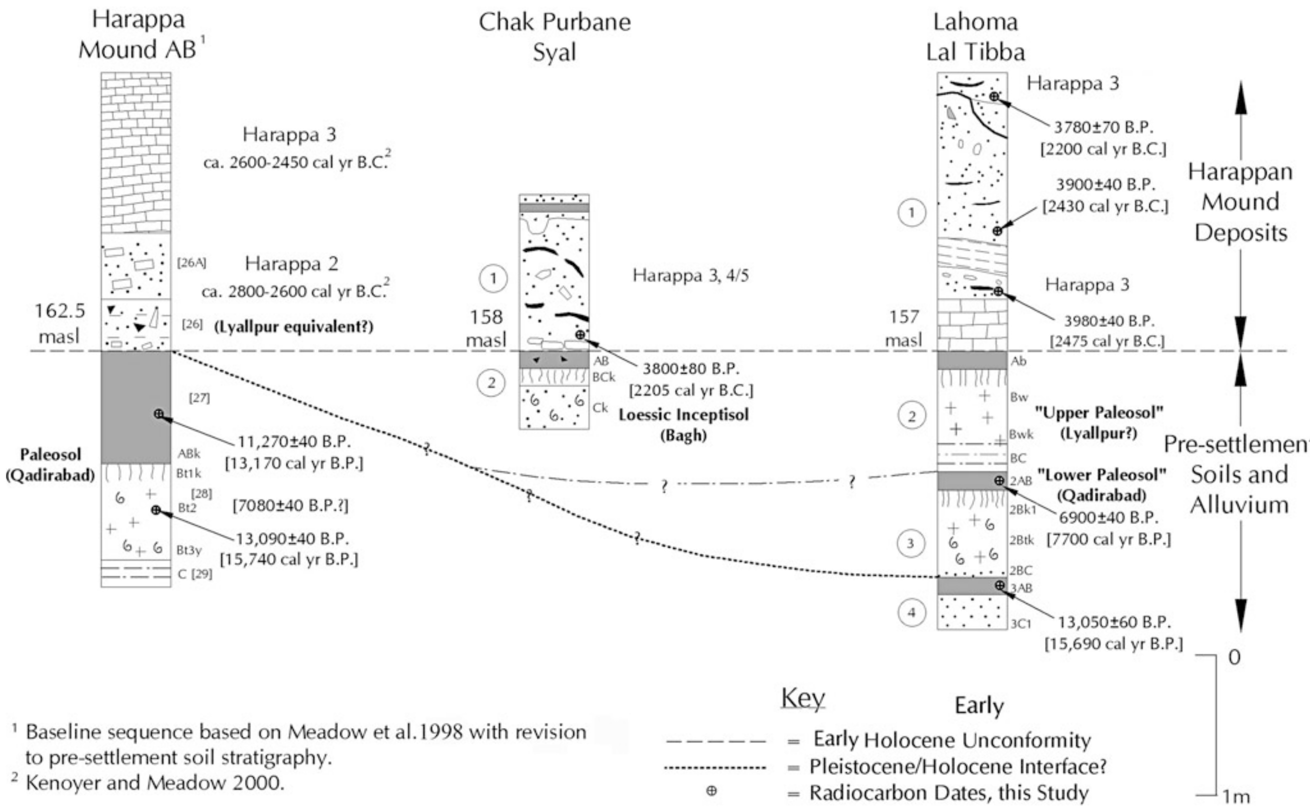
A.S. Gilbert (ed.), *Encyclopedia of Geoarchaeology*, DOI 10.1007/978-1-4020-4409-0,



Harappa, Figure 1 Location of the Harappa site in north-central Pakistan. The site is a mound complex on an abandoned channel of the Ravi River. The old bed of the Beas River and secondary Harappan sites along its reach are also shown.

urban complex). Dated sequences at stratified sites along the buried channel of the Beas River, south of the Ravi (Figure 1), facilitate regional, cyclically based reconstructions of Holocene paleoenvironmental conditions and landscape histories. In the vicinity of Harappa, the linkage of soil chronologies between secondary sites and Harappa underscores the stability of stable surfaces that gave rise to and ultimately accommodated Harappan settlements. Similarly, inter-site correlations of sediment-based alluviation regimes (indicative of surface burial and geomorphic dynamism) identified climatically triggered periods of landscape disequilibrium. The linked profiles (Figure 2) illustrate that while there is local variability in soil formation histories and intervening alluviation episodes, major phases of landscape stability – specifically those that formed extensive Harappan-era surfaces – are expressed on a regional scale. Such refined reconstructions enable researchers to sort out the complex influences of local vs. regional edaphic factors.

Advances in Harappan geoarchaeology reflect current exponential leaps in interdisciplinary research strategies as well as in the field's methodological and technological achievements. In general, the work in the Upper Indus has focused on developing baseline paleoenvironmental chronologies, structured by soil chronologies, and intervening alluvial successions that help explain settlement geography and differential site preservation. In southern Pakistan, along the Lower Indus, a geomorphology-centered approach is applied to correlate settlement variability with changing stream dynamics. That approach is conditioned by a history of fluvial geomorphic modeling in that area, which draws on the trunk stream's behavior of deep deposition coupled with periodic, often catastrophic, channel migrations. Finally the most recent methodological advances have integrated remote sensing strategies and advanced dating techniques (optically stimulated luminescence or OSL) to advance expansive extra-regional



Harappa, Figure 2 Site and regional stratigraphies of Harappa and other Upper Beas sites. A soil stratigraphic scheme indexed by radiocarbon dates was used to establish chronostratigraphic contemporaneity between Harappa and two secondary sites Kenoyer (2000).

reconstructions accounting for the emergence, florescence, and ultimate collapse of the Harappan culture across its geographic domain. A current model suggests that "climatic forcing" was the primary mechanism explaining decline of the civilization. The paradigm is structured on simulations for long-term weakening of the monsoon and thinning out of population centers, as documented by high-resolution shuttle radar topographic mapping (Giosan et al., 2012). Diminished precipitation resulted in substantially reduced stream flow and water supply. Data sets were taken to infer landward mobilization of Harappan populations, attendant shrinkage of the Harappan heartland, and profound changes in land use that were unsuccessful in the long run (Giosan et al., 2012). Such ecologically-based modeling, while beneficial, implicates the need for longer and more rigorous geoarchaeological testing on the site-specific and local levels. The development of even more sophisticated methodologies stands to extend the scope of geoarchaeological applications in the years to come.

Bibliography

Belcher, W. R., and Belcher, W. R., 2000. Geologic constraints on the Harappa archaeological site, Punjab Province, Pakistan. *Geoarchaeology*, **15**(7), 679–713.

Giosan, L., Clift, P. D., Macklin, M. G., Fuller, D. Q., Constantinescu, S., Durcan, J. A., Stevens, T., Duller, G. A. T., Tabrez, A. R., Gangal, K., Adhikari, R., Alizai, A., Filip, F., VanLaningham, S., and Syvitski, J. P. M., 2012. Fluvial landscapes of the Harappan civilization. *Proceedings of the National Academy of Sciences*, **109**(26), 1688–1694.

Kenoyer, J. M., 1998. *Ancient Cities of the Indus Valley Civilization*. Karachi: Oxford University Press.

Kenoyer, J.M. and Meadow, R.H. 2000. The Ravi Phase: a new cultural manifestation at Harappa (Pakistan). South Asian Archaeology 1997, ed. M. Taddei; and G. Demarco, *Rome* PP.55–76.

Meadow, R. H., Kenoyer, J. M., and Wright, R. P., 1998. *Harappa Archaeological Research Project: Harappa Excavations 1998*. Report submitted to the Director of Archaeology and Museums, Government of Pakistan, Karachi.

Pendall, E., and Amundson, R., 1990. Soil/landform relationships surrounding the Harappa archaeological site, Pakistan. *Geoarchaeology*, **5**(4), 301–322.

Possehl, G. L., 2002. *The Indus Civilization: A Contemporary Perspective*. Walnut Creek: Altamira.

Schuldenrein, J., Wright, R. P., Mughal, M. R., and Khan, M. A., 2004. Landscapes, soils, and mound histories of the Upper Indus Valley, Pakistan: new insights on the Holocene environments near ancient Harappa. *Journal of Archaeological Science*, **31**(6), 777–797.

Wheeler, R. E. M., 1947. Harappa 1946: the defenses and cemetery R-37. *Ancient India*, **3**, 58–130.

HARBORS AND PORTS, ANCIENT

Nick Marriner[1], Christophe Morhange[2], Clément Flaux[2] and Nicolas Carayon[3]
[1]CNRS, Laboratoire Chrono-Environnement UMR 6249, Université de Franche-Comté, Besançon, France
[2]Aix-Marseille Université, IUF, CEREGE UMR 6635, Aix-en-Provence, France
[3]Archéologie des Sociétés Méditerranéennes, UMR 5140, Lattes, France

Synonyms

Haven; Port; Roadstead

Definition

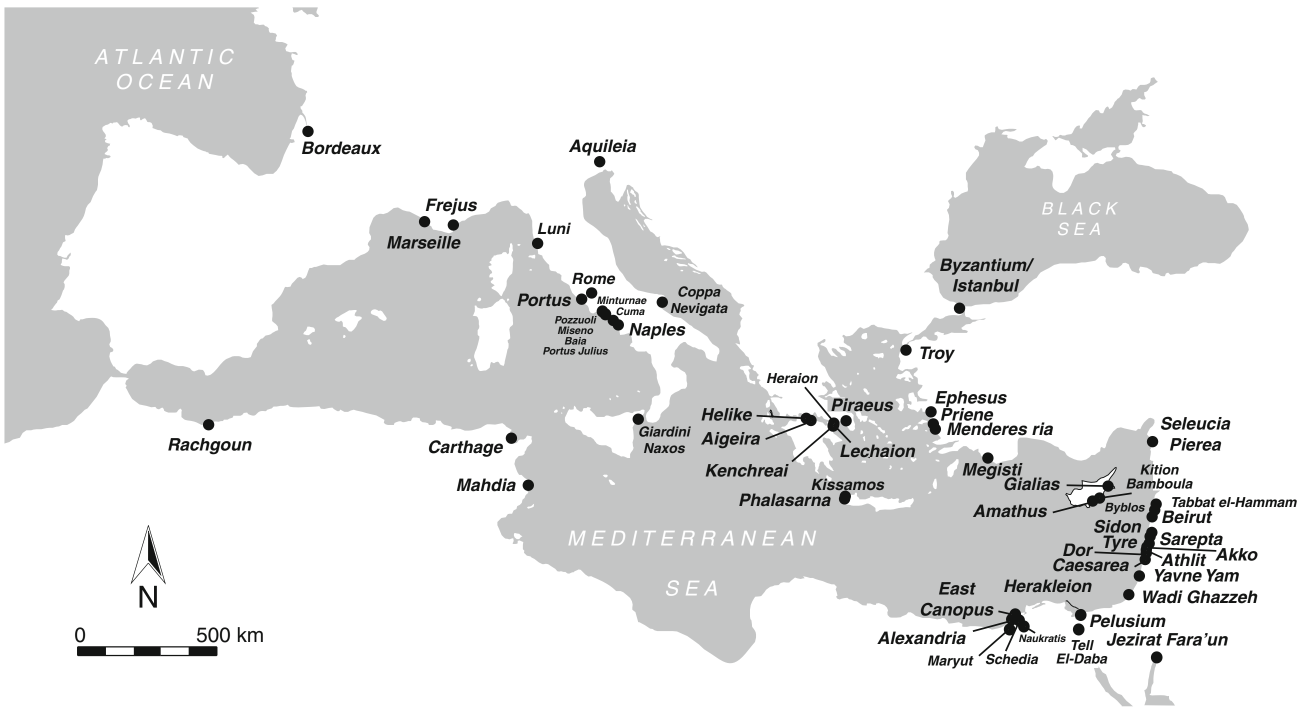
Coastal areas have been used as natural roadsteads at least since prehistoric times. In the Oxford English dictionary, a harbor is "a place on the coast where ships may moor in shelter, especially one protected from rough water by piers, jetties, and other artificial structures." This safe refuge can be either natural or artificial. As a result, the term "harbor" can often be ambiguous when it refers to a premodern context because it incorporates a plethora of landing site types, including offshore anchorages, in addition to different mooring facilities and technologies (Raban, 2009). Conceptions of ancient Mediterranean harbors have frequently been skewed by all-season harbor facilities such as Alexandria (Egypt), Piraeus (Greece), and Valletta (Malta) with their favorable geomorphological endowments. The archaeological record is, however, more complex. Port is derived from the Latin *portus* meaning "opening, passage, asylum, refuge." Drawing on multidisciplinary archaeological and geoscience tools, there has been a renewed interest in ancient harbors during the past 30 years, including the Indian Ocean (Rao, 1988), the Atlantic, Scandinavia (Ilves, 2009), the Mediterranean (Marriner and Morhange, 2007), and Africa (Chittick, 1979).

Introduction

Until recently, coastal sediments uncovered during Mediterranean excavations received very little attention from archaeologists, even though, traditionally, the received wisdom of *Mare Nostrum*'s history has placed emphasis on the influence and coevolution of physical geography in fashioning its coastal societies (Braudel, 2002; Stewart and Morhange, 2009; Martini and Chesworth, 2010; Abulafia, 2011). Before 1990, the relationships between Mediterranean populations and their coastal environments had been studied within a cultural-historical paradigm, where anthropological and naturalist standpoints were largely considered in isolation (Horden and Purcell, 2000). During the past 20 years, Mediterranean archaeology has changed significantly, underpinned by the emergence of a new culture-nature duality that has drawn on the North European examples of wetland and waterfront archaeology (Milne and Hobley, 1981; Coles and Lawson, 1987; Purdy, 1988; Coles and Coles, 1989; Mason, 1993; Van de Noort and O'Sullivan, 2006; Menotti and O'Sullivan, 2012). This built on the excavation of Alpine lake settlements in Switzerland and elsewhere from the 1850s onwards (Keller, 1866). Because of the challenges of waterfront contexts, the archaeological community is today increasingly aware of the importance of the environment in understanding the socioeconomic and wider natural frameworks in which ancient societies lived, and multidisciplinary research and dialogue have become a central pillar of most large-scale excavations (Walsh, 2004; Butzer, 2005; Butzer, 2008; Walsh, 2008).

It is against this backdrop that ancient harbor contexts have emerged as particularly novel archives, shedding new light on how humans have locally interacted with and modified coastal zones since the Neolithic (Marriner and Morhange, 2007). Their importance in understanding ancient maritime landscapes and societies (e.g., Gambin, 2004; Gambin, 2005; Tartaron, 2013) makes them one of the most discussed archaeological contexts in coastal areas (Figure 1). Around 6,000 years ago, at the end of the Holocene marine transgression, societies started to settle along "present" coastlines (Van Andel, 1989). Older sites were buried and/or eroded during this transgression (Bailey and Flemming, 2008). During the past ~4,000 years, harbor technology has evolved to exploit a wide range of environmental contexts, from natural bays and estuaries through to the completely artificial basins of the Roman and Byzantine periods. Although some of these ancient port complexes continue to be thriving transport centers, now, many millennia after their initial foundation, the vast majority have been completely abandoned, and their precise whereabouts, despite rich textual and epigraphic evidence, remain unknown. Although not the sole agent of cultural change, these environmental modifications indicate in part that long-term human subsistence has favored access to the open sea. Key to this line of thinking is the idea that societies have adopted adaptive strategies in response to the rapidly changing face of the coastal environment, and in many instances, harbor sites closely mirror modifications in the shoreline (e.g., Brückner et al., 2004). Nonetheless, it is important to emphasize that regional environmental change, although strong, must not be seen as the principal agent of cultural shifts and that site-specific explanations remain fundamental (Butzer, 1982).

During the 1960s, urban regeneration led to large-scale urban excavations in many coastal cities of the Mediterranean. It was at this time that the ancient harbor of Marseille (France) was rediscovered. Nonetheless, it was not until the early 1990s that two large-scale coastal excavations were undertaken at opposite ends of the Mediterranean in Marseille (Hesnard, 1994; Hesnard, 1995) and Caesarea Maritima in Israel (Raban and Holum, 1996). Both projects placed emphasis on the harbor archaeology and their articulation within the wider landscape. The first, at Caesarea Maritima, investigated a completely artificial Roman harbor complex on the Levantine coast, active between the first and second centuries AD (Reinhardt



Harbors and Ports, Ancient, Figure 1 Mediterranean harbor sites discussed in the text.

et al., 1994; Reinhardt and Raban, 1999; Raban, 2009). At Marseille, meanwhile, researchers set about reconstructing the archaeology and environmental history of the city's ancient harbor since the seventh century BC, founded in a naturally protected limestone embayment by Greek colonists from Ionia (Figure 2).

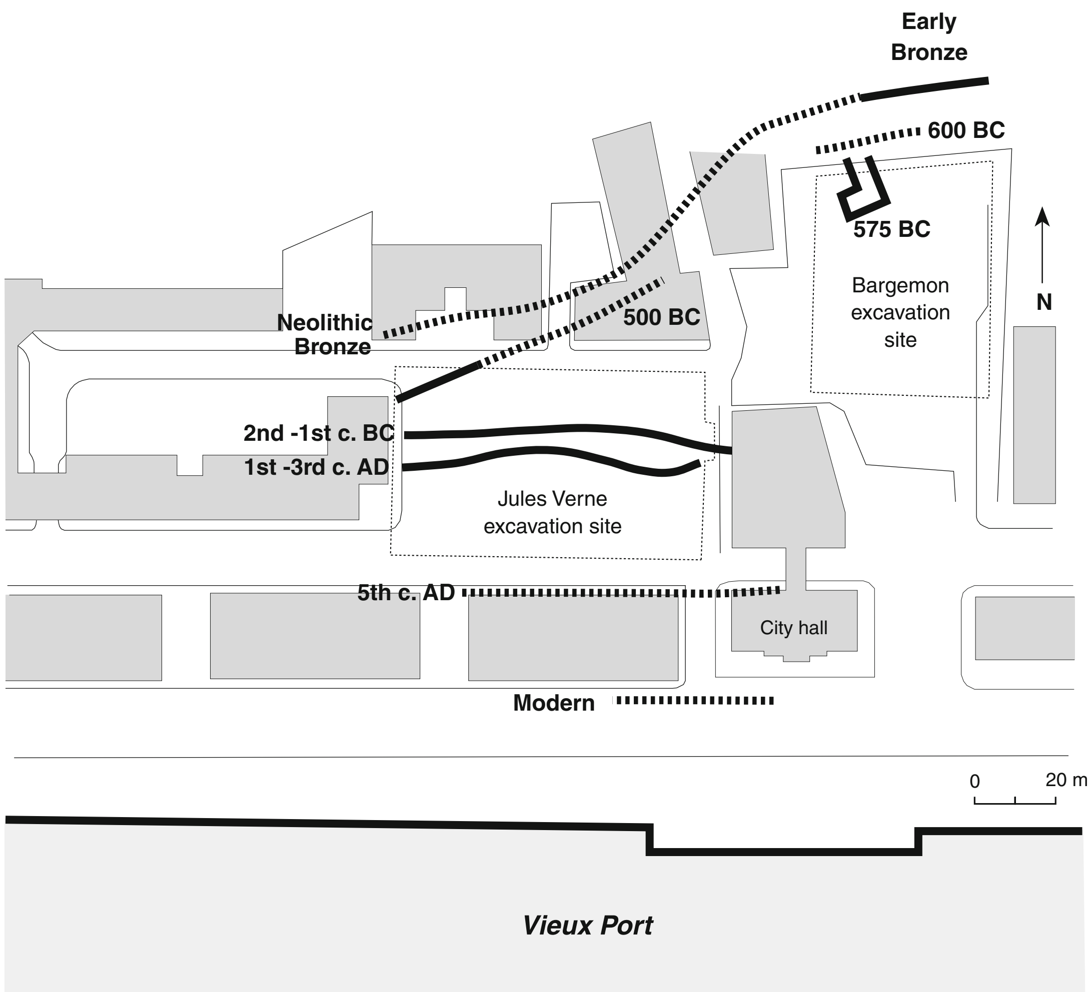
In contrast to deltaic areas, the smaller analytical scale of harbor basins meant that coastal changes could be studied not only with greater facility but also more finitely. The research at Marseille (Morhange et al., 2003) reconstructed a rapid shift in shoreline positions from the Bronze Age onwards and demonstrated the type of spatial resolution that can be obtained when large excavation areas are available for geoarchaeological study. These studies were unique in that, for the first time in a Mediterranean coastal context, both sought to embrace a multidisciplinary methodology. Investigative fields included not only archaeology but also geomorphology, geography, sedimentology, history, and biology (Raban and Holum, 1996; Hesnard, 2004). The waterlogged conditions were particularly conducive to environmentally contextualized analyses, and both studies demonstrated how coastal archaeology could benefit from being placed within a broader multidisciplinary framework.

Since these projects, there has been a great proliferation of studies looking into coastal and ancient harbor geoarchaeology (see Marriner and Morhange, 2007 for multiple references; Figure 1), building on pioneering archaeological work in the first half of the twentieth century (e.g., Negris, 1904a; Negris, 1904b; Paris, 1915; Jondet, 1916; Paris, 1916; Lehmann-Hartleben, 1923; Poidebard, 1939; Halliday Saville, 1941; Poidebard and Lauffray, 1951). Ancient harbor basins are particularly interesting because (1) they served as important economic centers and nodal points for maritime navigation (Casson, 1994; Arnaud, 2005); (2) there is generally excellent preservation of the material culture (Rickman, 1988; Boetto, 2012) due to the anoxic conditions induced by the water table; and (3) there is an abundance of source material for paleoenvironmental reconstruction (Marriner, 2009). Seaports are particularly interesting, as they allow us to understand how people "engaged with" the local environmental processes in coastal areas.

Here, we will explore the specific interest of harbor sediments in reconstructing ancient coastal landscapes and their evolution through time. In particular, we will discuss the stratigraphic evidence for these changes and set them within the wider context of coastal changes driven by various natural and anthropogenic forcing agents. We will also address present challenges and gaps in knowledge.

Harbor origins

The ease of transport via fluvial and maritime routes was important in the development of civilizations. At least three areas – the Indus, China, and Egypt – played an important role in the development of harbors and their infrastructure.



Harbors and Ports, Ancient, Figure 2 Coastal progradation in the ancient harbor of Marseille since Neolithic times. Chronostratigraphy and marine fauna fixed upon archaeological structures document a steady 1.5 m rise in relative sea level during the past 5,000 years. Sea level was broadly stable around the present datum between AD 1500 and the last century.

Egypt

It has been suggested that the Egyptians were one of the earliest Mediterranean civilizations to engage in fluvial and maritime transportation. Evidence for the use of boats in ancient Egypt derives from deepwater fish bones found at prehistoric hunter/gatherer campsites (Shaw et al., 1993). The earliest boats were probably rafts made of papyrus reeds, which enabled these societies to navigate between camps. It is speculated that wooden boats were adopted during Neolithic times, around the same time as the introduction of agriculture and animal husbandry. The rise of chiefdoms during the Egyptian Predynastic period (3700–3050 BC) was accompanied by the widespread adoption of boats as attested by art and pottery depictions (Fabre, 2004–2005). North of the First Cataract in Egypt, ships could travel almost anywhere along the Nile. On the delta, the then seven branches served as navigable waterways into the Eastern Mediterranean (Tousson, 1922; Stanley, 2007; Khalil, 2010). The Eastern Mediterranean was also a natural communications link for the major cultural centers of the Levant, Cyprus, Crete, Greece, and North Africa. In light of this, it is unsurprising that the works along the fluvial banks and coastlines of the Red Sea and Mediterranean were many and varied. During the third millennium BC, canals were excavated from the Nile to the valley temples of the Giza pyramids so that building materials could be transported (Fabre, 2004–2005; Butzer et al., 2013). Quays were also commonly established along the Nile, for instance, at fourteenth century BC Amarna, boats have been depicted parallel to shoreside quays equipped with bollards (Blackman, 1982a; Blackman, 1982b). An artificial quay dating to the second millennium BC is attested at Karnak, on the Nile (Lauffray et al., 1975; Fabre, 2004–2005). High sediment supply and rapid changes in fluvial systems mean that few conspicuous remains of these early riverine harbors are still visible, particularly on the delta (Blue and Khalil, 2010). In Mesopotamia, a similar evolution is attested (Heyvaert and Baeteman, 2008).

Navigation in the Red Sea during pharaonic times is a theme that has attracted renewed interest during the past 30 years, underpinned notably by the discovery of a number of exceptional coastal sites, shedding new light on the extent and chronology of human impacts in maritime areas. Extending for over 2,000 km from the Mediterranean Sea to the Arabian Sea, the Red Sea was a major communications link. Egyptian seafarers traveled along its shorelines during the Predynastic period and were probably the first to contact the peoples living on the Sudanese coast and around the Horn of Africa. Since the discovery of remains at Mersa/Wadi Gawasis in 1976, new findings have been made more recently at Ayn Soukhna, El-Markha, and Wadi al-Jarf (Tallet, 2009). In the absence of harbor excavations, much of the data available remain preliminary. At Mersa/Wadi Gawasis, archaeological data have documented evidence for some of the world's earliest long-distance seafaring, including bundled ropes, ships, and remnants of storage boxes used for the transport of goods. The site was used extensively during the Middle Kingdom (around 4,000–3,775 years ago), when seafaring ships departed from the harbor for trade routes along the African Red Sea coast (Bard and Fattovich, 2010; Hein et al., 2011).

The Indus Valley

On the Indian subcontinent, archaeological explorations during the past century have brought to light a large number of structures related to ancient harbor works and maritime activities (Rao, 1988). The Indus valley in particular has been a key focus of research, where high sediment supply in a context of rapidly changing deltaic environments is responsible for the landlocking of many ancient port sites (Gaur and Vora, 1999). The oldest reference to a harbor in India derives from a mid-third millennium Mesopotamian text mentioning boats from Meluhha that were anchored in Agade harbor (Kramer, 1964). Nonetheless, despite rich textual evidence, the exact location of many of these ancient harbor sites is equivocal. Most would have exploited riverbanks that served as natural harbors. Many of the best-studied examples derive from the region of Gujarat, which attests to significant paleoshoreline changes during the past 4,500 years (Gaur and Vora, 1999).

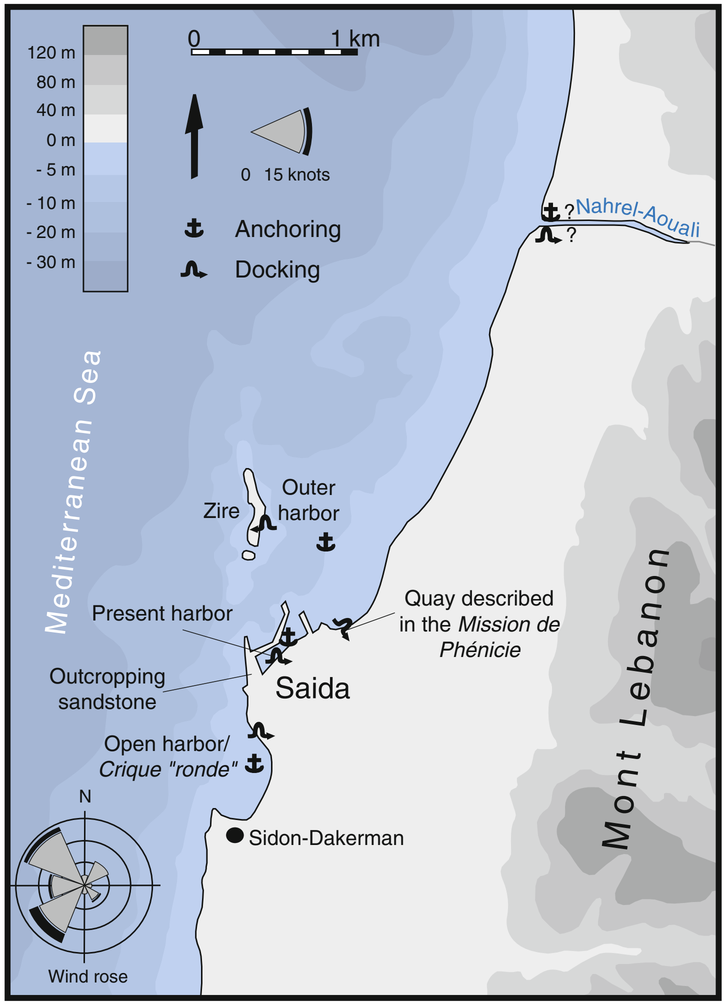
Archaeological sites of Harappan age (3000–1500 BC), including Lothal, Padri, and Bet Dwarka, have yielded particularly interesting archaeological records consistent with maritime activity (Gaur and Vora, 1999). Lothal, on the paleo-banks of the river Sabarmati, is one of the best-studied examples of a Harappan harbor city. The site presently lies 35 km from the coast at the head of the macrotidal Gulf of Cambay and is believed to have been an important trade center during the Harappan period (Rao, 1991). A number of Egyptian and Mesopotamian imports have been recovered from the site. Excavations have brought to light a brick basin of trapezoidal shape that measures 214 × 36 m and is 3.3 m deep. It has tentatively been labeled as the world's first dockyard (Rao, 1979), although these interpretations are not without contention (e.g., Gaur, 2000), and the basin presents striking similarities with water storage basins used throughout the region. Based on present knowledge, it is difficult to confirm that Lothal's basin was used as a harbor. Elsewhere in the Indus valley, Chalcolithic/Harappan landing platforms attributed to harbor works have been identified at Kuntasi and Inamgaon. Paleoenvironmental changes are seen as important causes of harbor abandonment.

China

Between 7000 and 5000 BC, agricultural villages and towns began to emerge and grow along the Yellow and Yangtze River basins and coasts. Research has focused on this transitional period because it corresponds to the onset of deltaic sedimentation and the emergence of agriculture and early complex societies (Zong et al., 2007; Chen et al., 2008). Ancient Chinese history is marked by three successive dynasties that became the roots of Chinese culture: the Xia Dynasty (2200–1766 BC), the Shang Dynasty (1766–1122 BC), and the Zhou Dynasty (1122–256 BC). Despite the importance and continuity of Chinese civilization, understanding of its harbors is relatively limited in western academic circles due to obvious language barriers. Nonetheless, the recent rediscovery of Hepu harbor of the Western Han Dynasty (206 BC to 25 AD) is particularly promising in shedding new light on this question. Now located within Beihai City in south China's Guangxi Zhuang Region, recent archaeological work suggests that Hepu harbor – probably the oldest seaport in China – served as a very important "marine silk road." This navigation link allowed western goods to be transported into the vast continental interior of Asia.

Early Mediterranean harbors

Our understanding of early harbors is poor. In the Mediterranean, the first artificial structures appear to date to the Middle/Late Bronze Age. For example, submerged boulder piles are attested at Yavne-Yam, a Middle Bronze Age site on the coast of Israel; these suggest premeditated human enterprise to improve the quality of the natural anchorage (Ezra Marcus, personal communication). Recent geoarchaeological work in Sidon (Lebanon) has tentatively dated the presence of a semi-protected cove beginning around 4410 ± 40 BP (2750–2480 cal BC; Marriner et al., 2006b; Marriner, 2009). This sedimentological unit has been interpreted as a Middle Bronze Age to Late Bronze Age proto-harbor, with possible reinforcement of the shielding sandstone ridge improving the quality of the natural anchorage. It is suggested that small boats were beached, with larger vessels being anchored in the outer harbor of Zire (Frost, 1973; Carayon, 2008; Figure 3).



Harbors and Ports, Ancient, Figure 3 Sidon's ancient harbor areas (Adapted from Carayon (2008) and Marriner (2009)).

At Kommos, in southern Crete, a large building with six galleries (Puglisi, 2001) has been interpreted as a hangar for the dry-docking of Minoan ships during the winter months. This building, dated to the fifteenth century BC, is an illustration of Minoan harbor construction even though, in this instance, it had no direct impact upon the quality of the anchorage haven.

After this period, the maritime harbors of the ancient Mediterranean evolved in four broad technological leaps.

Bronze Age to early Iron Age ashlar header technology

A double ashlar wall infilled with stones is a harbor construction method common to the Phoenicians; it is known as the pier-and-rubble technique (Raban, 1985). This system has been noted in an eleventh century BC layer at Sarepta, Lebanon (Markoe, 2000). Van Beek and Van Beek (1981) have suggested that this technique is Levantine in origin and that it spread from the Late Bronze Age Levant to the western Punic colonies, Greece, and Roman North Africa, where it can be found as late as the sixth century AD. The use of ashlar techniques is well attested in the Persian period harbor of Akko (Israel), the Hellenistic harbor at Amathus in Cyprus (Empereur and Verlinden, 1987), and the Roman quay at Sarepta, Lebanon (Pritchard, 1978), Dor, and Athlit (Israel). Iron Age Athlit is one of the best-studied Phoenician harbors (Haggi, 2006; Haggi and Artzy, 2007). The northern harbor's mole extends about 100 m into the sea. It is about 10 m wide and constitutes two parallel ashlar headers that are 2–3 m in width. A fill of rubble and stones was placed between the ashlar walls. This form of construction improved the stability of the mole against high-energy waves. The mole was placed on a foundation of ballast pebbles of various sizes. Underwater excavations have revealed that the layer of pebbles extends more than 5 m beyond the outer side of each wall, a total width of over

20 m. Radiometric dating of wood fragments constrains this Phoenician structure to the ninth century BC (Haggi, 2006), although paradoxically there is very little pottery dating from this period (Michal Artzy, personal communication). A similar example is also known from the Syrian coast at Tabbat el-Hammam, where the archaeological evidence supports a ninth/eighth century BC age (Braidwood, 1940).

Depending on the time and culture, different variations are noted in the use of headers. From the fifth century BC, metal links were used to reinforce blocks (e.g., Sidon and Beirut). At Amathus (Cyprus) during Hellenistic times, the header masonry was built upon a ballast base of disorganized blocks.

Cothons

Archaeologists refer to the sites of Carthage (Tunisia), Mahdia (Tunisia), Phalasarna (Crete), Jezirat Fara'un (Egypt), and Lechaion (Greece) as "cothon" harbors. The Greek term was applied to the harbor at Carthage by Strabo and Appian, the original meaning of "drinking cup" which is metaphorically appropriate to the protected harbor basin. Carthage is the only site that has been referred to as a "cothon" in ancient texts, although a Punic etymology has not yet been supported, meaning it is difficult to propose that the concept was Carthaginian in origin or that all harbors built into the shoreline in the same manner were felt to be variations on a "cothon" (John Oleson, personal communication). Nowadays, specialists agree that the term can be associated with an artificially dug harbor basin linked to the sea via a man-made channel (Carayon, 2005). The design solves some of the problems involved in building a harbor along a shallow, featureless coastline, or on the bank of a river, and a number of cultures appear to have adopted this solution, from the Bronze Age onwards. Some authors have suggested that Trajan's basin at Portus also qualifies as a cothon, in addition to some of the proposed Etruscan harbor basins associated with river mouths (John Oleson, personal communication). It would appear that the carving of a cothon is a simple but energy-consuming technique used to create a particularly well-sheltered basin. This type of infrastructure poses three problems: (1) rapid silting up in a confined environment; (2) the carving of a basin in rocky outcrops or clastic coastlines, which is energy consuming; and (3) maintaining a functional channel outlet to the sea in a clastic coast context. Despite these shortcomings, the cothon persisted for many centuries (Carayon, 2008). A Latin author, writing in the fifth century AD, noted that this type of harbor was common at this time: "*ut portus scilicet faciunt*" (Deutero-Servius, *Aeneidos*, I, 421).

Hydraulic concrete

Pre-Roman ashlar block methods continued to be used throughout the Roman era. Nonetheless, another technique was introduced during the second century BC (Gazda, 2001) that completely revolutionized harbor design and construction – the use of hydraulic concrete. This technological breakthrough meant that natural roadsteads were no longer a prerequisite to harbor loci, and completely artificial ports, enveloped by imposing concrete moles, could be located on open coasts (Hohlfelder, 1997). The material could be cast and set underwater. Roman architects and engineers were free to create structures in the sea or along high-energy shorelines (Brandon et al., 2005; Brandon et al., 2010). Pozzolana facilitated the construction of offshore basins such as Claudius's harbor at Portus of Rome (Testaguzza, 1970). The Roman author Vitruvius (first century BC) provided an inventory of harbor construction techniques (Vitruvius, *De Architectura*, V, 12).

Romano-Byzantine harbor dredging

Vitruvius gave a few brief accounts of dredging, although direct archaeological evidence has, until now, remained elusive. The ancient harbors of Marseille and Naples have both undergone widespread excavations (Figure 4; Hesnard, 1995; Giampaola et al., 2004), and extensive multidisciplinary datasets now exist for the two sites. At Tyre and Sidon, geoarchaeological research has led to the extraction of 40 cores that have facilitated a chronostratigraphic reconstruction of basin silting (Marriner et al., 2005; Marriner and Morhange, 2006a; Morhange and Marriner, 2010a). Why were ancient harbors dredged? On decadal timescales, continued silting induced a shortening of the water column. De-silting infrastructure (Blackman, 1982a; Blackman, 1982b), such as vaulted moles, partially attenuated the problem, but in the long term, these appear to have been relatively ineffective. In light of this, repeated dredging was the only means of maintaining a practicable draft depth and ensuring long-term harbor viability. At Marseille, although dredging phases are recorded from the third century BC onwards, the most extensive enterprises were undertaken during the first century AD, at which time huge volumes of sediment were extracted. At the excavations of Naples, absence of pre-fourth century BC layers has been linked to extensive dredging between the fourth and second centuries BC (Carsana et al., 2009). Unprecedented traces 165–180 cm wide and 30–50 cm deep attest to powerful dredging technology that scoured into the volcanic substratum, completely reshaping the harbor bottom. Notwithstanding the scouring of harbor bottoms, this newly created space was rapidly infilled and necessitated regular intervention. Repeated dredging phases are attested up until the late Roman period, after which time the basin margins were completely silted up. At Marseille, three dredging boats have been unearthed (Pomey, 1995). The vessels were abandoned at the bottom of the harbor during the first and second centuries AD. They are characterized by an open central well that is inferred to have accommodated the dredging arm.

It was not until the Industrial Revolution in England that cement and iron structures were developed on

Harbors and Ports, Ancient, Figure 4 Harbor dredging in Naples (Photograph: D. Giampaola, Archaeological Superintendence of Naples).

a large scale (Palley, 2010). In 1756, Smeaton made the first modern concrete (hydraulic cement) by adding pebbles as a coarse aggregate and mixing powdered brick into the cement. In 1824, Aspdin invented Portland cement by burning ground limestone and clay together. The Frenchman Monier invented reinforced concrete in 1849 using imbedded steel. It can withstand heavy loads because of its tensile and compressional strengths. Reinforced concrete was widely used in railway ties, pipes, floors, arches, bridges, and ports.

Geoarchaeology of harbor basins: tools and methods

Over the past two decades, ancient harbors have attracted interest from both the archaeological and earth science communities. In tandem with the development of rescue archaeology, particularly in urban contexts, the study of sedimentary archives has grown into a flourishing branch of archaeological inquiry (Milne, 1985; Leveau et al., 1999; Milne, 2003; Walsh, 2004; Leveau, 2005). The growing corpus of sites and data demonstrates that ancient harbors constitute rich archives of both the cultural and environmental pasts. Ancient harbor sediments are particularly rich in research objects (archaeological remains, bioindicators, macrorests, artifacts, etc.), and they yield insights into the history of human occupation at a given site, coastal changes, and the natural processes and hazards that have impacted these waterfront areas (Reinhardt et al., 2006; Bottari and Carveni, 2009; Morhange and Marriner, 2010b; Bony et al., 2012).

Ancient harbors are both natural and constructed landscapes and, from a geoarchaeological perspective, comprise three elements of note.

The harbor basin

In architectural terms, the harbor basin is characterized by its artificial structures, such as quays, moles, and sluice gates (Oleson, 1988; Oleson and Branton, 1992). Since the Bronze Age, there has been a great diversity in harbor infrastructure in coastal areas, reflecting changing technologies and human needs. These include, for instance, the natural pocket beaches serving as proto-harbors (Frost, 1964; Marcus, 2002a; Marcus, 2002b), through the first Phoenician mole attributed to around 900 BC (Haggi and Artzy, 2007), to the grand offshore constructions of the Roman period made possible by the discovery of hydraulic concrete (Oleson et al., 2004).

In their study of harbor landscapes, geoarchaeologists are also interested in the sedimentary contents of the basin and relative sea-level changes.

Ancient harbor sediments

Port basins constitute unique coastal archives. Shifts in the granularity of these deposits indicate the degree of harbor protection, often characterized by a rapid accumulation of heterometric sediments following a sharp fall in water competence brought about by the installation of artificial harbor works. The harbor facies is characterized by three poorly sorted fractions: (1) human waste products, especially at the base of quays and in areas of unloading (harbor depositional contexts are particularly conducive to the preservation of perishable artifacts such as leather and wood); (2) poorly sorted sand; and (3) an important fraction (>90 %) of silt that signifies the sheltered environmental conditions of the harbor. They are also particularly pertinent archives for reconstructing the history of heavy metal pollution at coastal settlements (e.g., Véron et al., 2006). Harbor basins are characterized by rapid accumulation rates. For instance, sedimentation rates of up to 20 mm/year have been recorded in undredged areas of the Graeco-Roman harbor of Alexandria (Goiran, 2001). High-resolution study of the bio- and lithostratigraphical fractions can help shed light on the nature of ancient harbor works, such as at Tyre (Marriner et al., 2008) or Portus (Goiran et al., 2010). Recent research has sought to characterize and date these chronostratigraphic phases using the unique sedimentary signature that each technology brings about (Marriner and Morhange, 2007; Marriner, 2009). In the broadest sense, these are characterized by an evolution from natural roadsteads before the Bronze Age towards completely artificial seaport complexes from the Roman period onwards.

Relative sea-level changes, the paleo-water column, and ship circulation

Nowadays, most ancient harbors are completely infilled with sediments – e.g., the Roman harbor of Luni at the mouth of the river Magra (Bini et al., 2009) or the Roman harbor of Aquileia (Arnaud-Fassetta et al., 2003). Harbor sediments are particularly conducive to the preservation of biological remains. Within this context, it is possible to identify and date former sea-level positions using biological indicators fixed to quays, that, when compared with the marine bottom, allow the height of the paleo-water column to be estimated (Laborel and Laborel-Deguen, 1994; Morhange et al., 2013). Such relative sea-level data are critical in understanding the history of sedimentary accretion in addition to estimating the draft depth for ancient ships (Pirazzoli and Thommeret, 1973; Morhange et al., 2001; Boetto, 2012). Archaeological work undertaken upon ancient wrecks suggests that the largest fully loaded ships during antiquity required a draft of less than 3 m (Casson, 1994; Pomey and Rieth, 2005). These two reference levels, the paleo-sea level and sediment bottom, are mobile as a function of crustal movements – e.g., local-scale neotectonics (Stiros et al., 1996; Stiros, 1998; Evelpidou et al., 2011), regional isostasy (Lambeck et al., 2004), sediment budgets (Vött et al., 2007; Devillers, 2008), and human impacts such as dredging (Marriner and Morhange, 2006b). All these factors can potentially impact the available accommodation space for sediment accretion.

Sediments versus settlements

As outlined above, one of the key problems posed by artificially protected harbors relates to accelerated sediment trapping. In the most acute instances, it could rapidly reduce the draft depths necessary in accommodating large ships (Pomey and Rieth, 2005). From a cultural perspective, therefore, harbors were important "economic landscapes," and many changes in harbor location can be explained functionally by the need to maintain an interface with the sea in the face of rapid sedimentation. The best example of this coastal dislocation derives from Aegean Anatolia (Brückner et al., 2005). Delta areas in particular serve as excellent geo-archives to understand and analyze the impacts of rapidly evolving settlement phases.

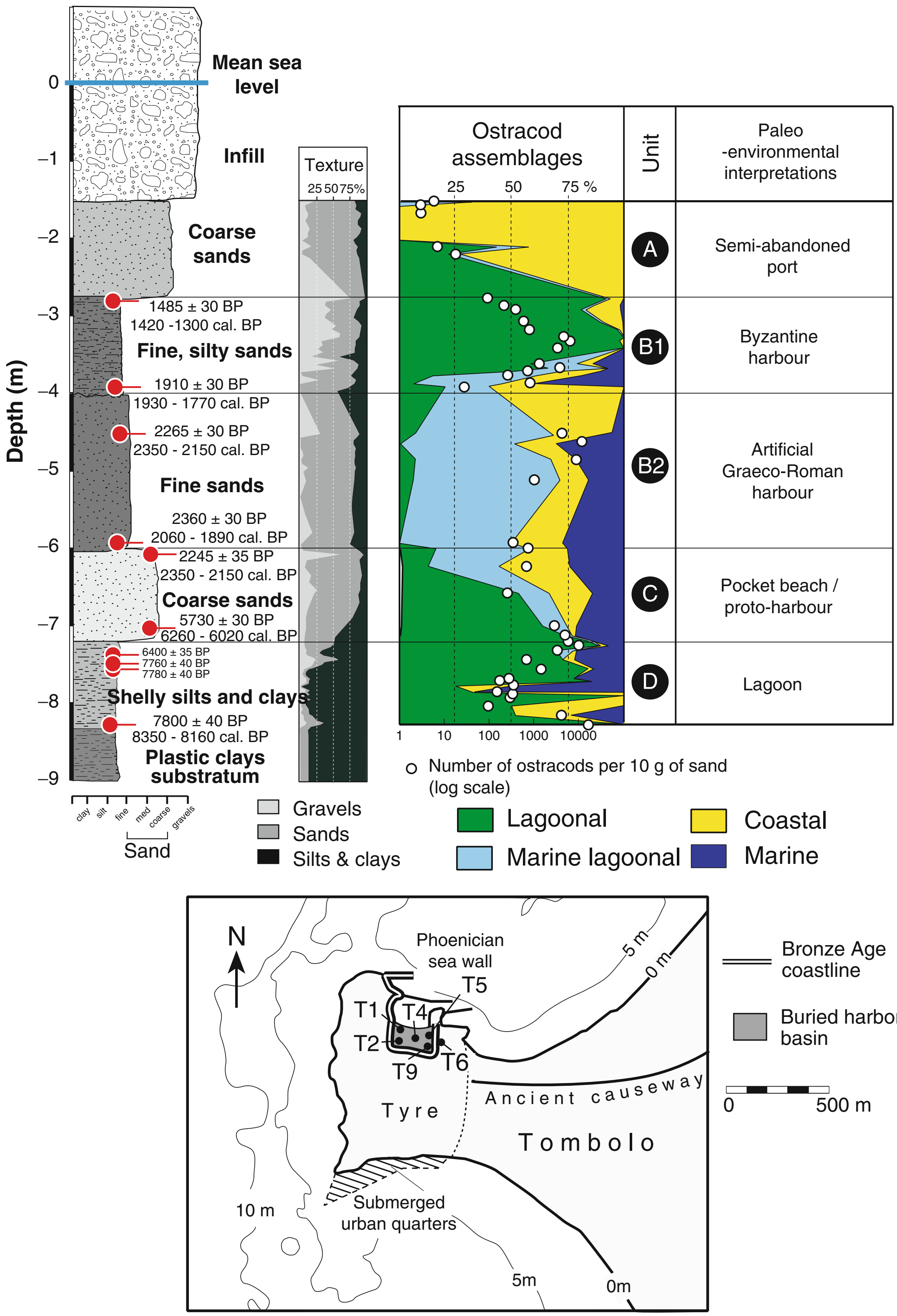
It is important to set these geoarchaeological results within a wider spatiotemporal framework using archaeological data from coastal and hinterland valley areas. Changes in sediment supply at the watershed scale are particularly important in understanding base-level changes in deltaic and coastal contexts, as is the case of the Gialias in Cyprus (Devillers, 2008) or the paleo-island of Piraeus (Goiran et al., 2011). Probing the rates of progradation is also key to understanding the timing, origin (climate or human forcings), and rhythm of local and basin-scale erosion.

Ancient harbor stratigraphy, terminology and research goals

During the past 20 years, multidisciplinary inquiry has allowed a better understanding of where, when, and how ancient Mediterranean harbors evolved. This is set within the wider context of a new "instrumental" or "quantitative revolution" towards the environment. A battery of research tools is available, tools that broadly draw on geomorphology and the sediment archives located within this landscape complex (Marriner and Morhange, 2007).

Where?

The geography of ancient harbors constitutes a dual investigation that probes both the location and the extension of the basins. Biostratigraphical studies of sediments, married with a GIS investigation of aerial photographs and satellite images, can be used to reconstruct coastal evolution and identify possible anchorage areas (Ghilardi and Desruelles, 2009). Traditionally, urban contexts have been particularly problematic for accurate archaeological studies because the urban fabric can hide many of the most important landscape features. In such instances, chronostratigraphy can be particularly useful in reconstructing coastal changes (Morhange et al., 2003). For example, litho- and biostratigraphical studies of cores drilled in the city center of Tyre attest to a well-sheltered port basin between the Hellenistic and Byzantine periods, today buried beneath the modern market by thick sediment tracts. The chronostratigraphy demonstrates that during antiquity, the harbor was approximately twice as large as present (Figure 5). This approach helps not only in reconstructing ancient shorelines and changes through time (e.g., as at Ephesus, Priene, Frejus, Alexandria, or Pelusium on the Nile Delta) but can also aid in relocating



Harbors and Ports, Ancient, Figure 5 Chronostratigraphic evolution of Tyre's ancient northern harbor since the Bronze Age (core T9).

ports for which no conspicuous archaeological evidence presently exists, as in the case of Cuma (Stefaniuk and Morhange, 2005) or Byblos (Stefaniuk et al., 2005).

Geophysical techniques can also provide a great multiplicity of mapping possibilities, notably in areas where it is difficult to draw clear parallels between the archaeology and certain landscape features (Nishimura, 2001). Because geophysical techniques are nondestructive, they have been widely employed in archaeology and are gaining importance in coastal geoarchaeology (Hesse, 2000) and ancient harbor contexts (Boyce et al., 2009). Very rapid and reliable information can be provided on the location, depth, and nature of buried archaeological features before excavation. At Alexandria, geophysical surveys have allowed Hesse (1998) to propose a new hypothesis for the location of the Heptastadium. Hesse suggests that the causeway linking Pharos to the mainland was directly tied into the city's ancient road network. In this instance, the findings have since been corroborated by sedimentological data from the tombolo area (Goiran, 2001). Stratigraphic data are therefore critical in providing chronological insights into environmental changes and coastal processes. Such a dual approach has also been successfully employed at Portus, one of the ancient harbors of Rome. Large areas of the seaport and its fringes have been investigated using coastal stratigraphy (Bellotti et al., 2009; Giraudi et al., 2009; Goiran et al., 2010; Di Bella et al., 2011; Mazzini et al., 2011; Salomon et al., 2012), geophysics, and archaeological soundings (Keay et al., 2005; Keay et al., 2009; Keay and Paroli, 2011), yielding fresh insights into the harbor's coastal infrastructure and functioning. On the Tiber delta, geophysics has also been used to accurately map the progradation of the coastal ridges. Bicket et al. (2009) have demonstrated that the Laurentine ridge, ~1 km inland from the modern coastline, constitutes the Roman shoreline of the Tiber delta.

When and how?

Chronostratigraphy is essential in understanding modifications in harbor technology and the timing of human impacts, such as lead pollution from the Bronze Age onwards (Véron et al., 2006) or ecological stresses demonstrated by changes in faunal assemblages (Leung Tack, 1971–72). The overarching aim is to write a "sedimentary" history of human coastal impacts and technologies, using quantitative geoscience tools and a standardized stratigraphic framework (e.g., sequence stratigraphy). Research in the eastern and western Mediterranean attests to considerable repetition in ancient harbor stratigraphy, both in terms of the facies observed and their temporal envelopes. There are three distinct facies of note: (1) middle-energy beach sands at the base of each unit (e.g., the proto-harbor), (2) low-energy silts and gravels (e.g., the active harbor phase), and (3) coarsening up beach sands or terrestrial sediments which cap the sequences (e.g., post-harbor facies). In the broadest terms, this stratigraphic pattern represents a shift from natural coastal environments to anthropogenically modified contexts, before a semi- or complete abandonment of the harbor basin.

There are a number of stratigraphic surfaces that are key to understanding the evolution of ancient harbor basins.

The maximum flooding surface (MFS)

Ancient harbors form integral components of the highstand parasequence (aggradational to progradational sets). For the Holocene coastal sequence, the maximum flooding surface (MFS) represents the lower boundary of the sediment archive. This surface is broadly dated to around 6000 cal BP and marks the maximum marine incursion (Stanley and Warne, 1994). It is associated with the most landward position of the shoreline. In the eastern Mediterranean, it is contemporaneous with the Chalcolithic period and the Early Bronze Age. Indeed, the MFS along the Levantine coast clearly delineates the geography of early coastal settlements from this period (Raban, 1987).

Natural beach facies

The MFS is overlain by naturally aggrading beach sands, a classic feature of clastic coastlines. Since around 6000 cal BP, relative sea-level stability has impinged on the creation of new accommodation space, leading to the aggradation of sediment strata. This is particularly pronounced in sediment-rich coastal areas such as deltas and at the margins of fluvial systems. Where this sedimentation continued unchecked, a coarsening upward of sediment facies is observed, consistent with high-energy wave dynamics in proximity to mean sea level. For example, Gaza bears witness to important coastal changes since the Bronze Age. During the mid-Holocene, the coast comprised estuaries at the outlets of major wadi systems. This indented coastal morphology spawned important maritime settlements such as Tell es-Sakan and Tell al-'Ajjul at the outlet of Wadi Ghazzeh, which probably served as a natural harbor. During the same period, the rate of sea-level rise slowed, leading to the formation of the Nile Delta and small, local deltas along the coasts of Sinai and Palestine. From the first millennium BC onwards, the coast was regularized by infilling of the estuaries, and the harbor sites became landlocked. In response, new cities, such as Anthedon, were founded on a Quaternary ridge along the present coastline (Morhange et al., 2005).

The harbor foundation surface (HFS)

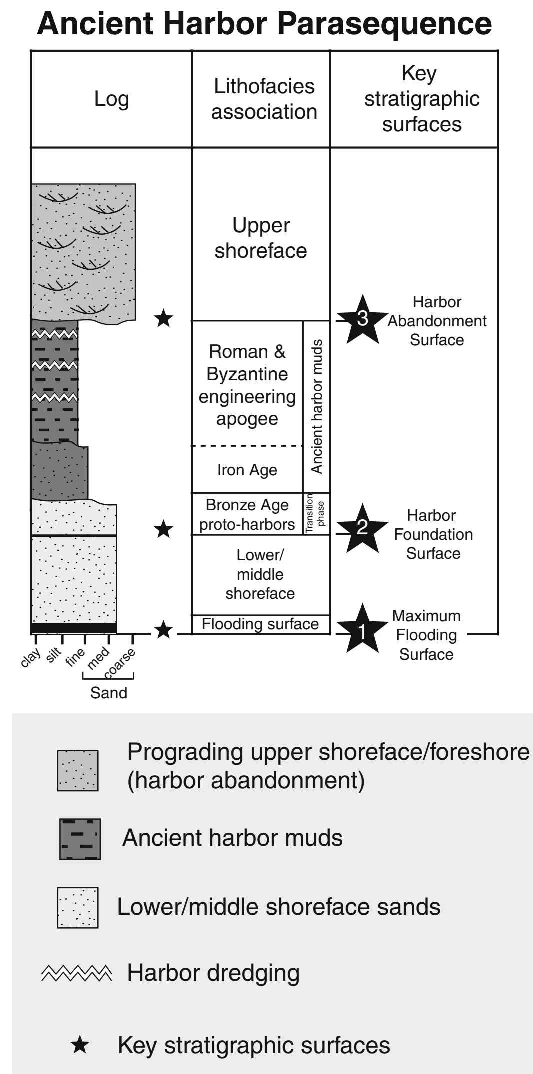
This surface marks important human modification of the sedimentary environment, characterized by the transition from coarse beach sands to finer-grained harbor sands and silts (Marriner and Morhange, 2007). This surface corresponds to the construction of artificial harbor works and, for archaeologists, is one of the most important surfaces to date the foundation of the harbor.

The ancient harbor facies (AHF)
The AHF corresponds to the active harbor unit. This artificialization is reflected in the sedimentary record by lower-energy facies consistent with a barring of the anchorage by artificial means. Harbor infrastructure (quays, moles, and jetties) accentuated the sediment sink properties by attenuating the swell and marine currents leading to a sharp fall in water competence. Research has demonstrated that this unit is by no means homogeneous, with harbor infrastructure and the nature of sediment sources playing a key role in shaping facies architecture. Of note is the granulometric paradox of this unit consisting of fine-grained silts juxtaposed with coarse gravels made up of ceramics and other urban waste.

In some rare instances, a proto-harbor phase (PHP) precedes the AHF. Before the major changes characteristic of the AHF, biosedimentological studies have elucidated moderate signatures of human presence when societies exploited natural low-energy shorelines requiring little or no human modification. For instance, coastal stratigraphy has demonstrated that the southern cove of Sidon, around Tell Dakerman, remained naturally connected and open to the sea throughout antiquity (Poidebard and Lauffray, 1951; Marriner et al., 2006a; Marriner et al., 2006b). The PHP interface is by no means transparent, particularly in early Chalcolithic and Bronze Age harbors, and the astute use of multiproxy data is required (Figure 6).

During the Late Bronze Age and Early Iron Age, improvements in harbor engineering have been recorded by increasingly fine-grained facies. Plastic clays tend to be the rule for Roman and Byzantine harbors, and sedimentation rates 10–20 times greater than naturally prograding coastlines are recorded. The very well-protected Roman harbors of Alexandria, Marseille, and Frejus (Gébara and Morhange, 2010) all comprise plastic marine muds consisting of 90 % silts and a coarse gravel fraction of human origin. Significant increases in sedimentation rates can also be attributed to human-induced increases in the supply term, for example, anthropogenic changes in the catchments of supplying rivers (deforestation, agriculture), erosion of mudbrick urban constructions (Rosen, 1986), and finally use of the basins as waste dumps. This underlines the importance of an explicit source-to-sink study integrating both the coastal area and the upland hinterland. Such high rates of harbor infilling were potentially detrimental to the medium- to long-term viability of harbor basins and impinged on the minimum 1 m draft depth.

The harbor abandonment surface (HAS)
This surface marks the "semi-abandonment" of the harbor basin. Recent studies have focused upon the role of natural hazards in explaining the decline or destruction of ancient Mediterranean harbors. While these factors may have had a role to play, it seems that the financial weight of maintaining harbor works in the face of the Mediterranean's shifting political and economic makeup was simply too burdensome (Raban, 2009). A relative decline in harbor works after the late Roman and Byzantine periods is



Harbors and Ports, Ancient, Figure 6 Chronostratigraphic evolution of ancient Mediterranean harbors in coastal areas.

characterized by a return to "natural" sedimentary conditions comprising (1) coarse-grained sands and gravels in a coastal context and (2) terrestrial facies in fluvial environments. Following hundreds to thousands of years of artificial confinement, reconversion to a natural coastal parasequence is sometimes expressed by high-energy upper shoreface sands. This shoreline progradation significantly reduced the size of the basins, often landlocking the heart of the anchorages beneath thick tracts of coastal and fluvial sediments.

Ancient harbor case studies: from natural to artificial ports

Today, it is recognized that harbors should be studied within broader regional frameworks using a multidisciplinary methodology (Carayon, 2008; Blackman and Lentini, 2010). There is great variety in harbor types, and, broadly speaking, three areas or physical processes are important in influencing harbor location and design: (1) geographical situation, (2) site and local dynamics, and (3) navigation conditions dictated by the wind and wave climate. The diversity of contexts investigated during the past 20 years has brought to light some striking patterns. Numerous processes are important in explaining how these have come to be preserved in the geological record, including the distance from the present coastline, position relative to present sea level, and geomorphology (Marriner and Morhange, 2007). Ancient harbors can be divided into six non-exhaustive types on the basis of preservation. Sediment supply, human impacts, crustal changes, and coastal energy dynamics are significant in explaining how ancient harbors have been preserved in the geological record (Bony, 2013).

Drowned harbors

Drowned cities and harbors have long captured the public imagination and inspired research (Marinatos, 1960; Frost, 1963; Flemming, 1971; Bailey and Flemming, 2008), fueled by mediatized legends such as Atlantis (Collina-Girard, 2001; Gutscher, 2005) and the "biblical flooding" of the Black Sea (Yanko-Hombach et al., 2007a; Yanko-Hombach et al., 2007b; Ravilious, 2009; Buynevich et al., 2011).

After the Last Glacial Maximum, when global sea level lay around 120 m below present, transgression of the continental platform gradually displaced coastal populations landwards until broad sea-level stability led to a sedentarization of populations along present coastlines (Van Andel 1989). The continental shelf between Haifa and Atlit (Israel) is one of the best-studied examples (Galili et al., 1988; Sivan et al., 2001). A series of submerged archaeological sites dating from the Pre-Pottery Neolithic B (8000 BP) and late Neolithic (~6500 BP) were found at depths of 12 to 8 m and 5 to 0 m, attesting to the postglacial transgression of the Levantine coastline. Since 6000 cal BP, coastal site and port submersion can be attributed to crustal mobility (e.g., historical subsidence in eastern Crete and uplift on the western coast) and/or sediment failure in deltaic contexts.

For example, on the western margin of the Nile Delta of Egypt, the coastal instability of the Alexandria area is responsible for a ~5 m drowning of archaeological remains since antiquity (Empereur and Grimal, 1997; Goddio et al., 1998; Goiran, 2001; Fabre, 2004–2005). The subsidence has been variously attributed to seismic movements (Guidoboni et al., 1994) and Nile Delta sediment loading (Stanley et al., 2001; Stanley and Bernasconi, 2006). Approximately 22 km east of Alexandria, around Abu Qir bay, an ~8 m collapse of the former Canopic lobe of the Nile is responsible for the drowning of two ancient seaport cities, Herakleion and East Canopus, during the eighth century AD (Tousson, 1922; Stanley et al., 2001; Stanley et al., 2004a; Stanley et al., 2004b).

Italy's Phlegraean Fields volcanic complex testifies to a very different crustal context that has led to a series of yo-yo land movements during the late Holocene. The ancient ports of Miseno, Baia, and Portus Julius are located inside a caldera (Gianfrotta, 1996; Scognamiglio, 1997; Figure 7). Since Roman times, tectono-volcanism inside this collapsed volcanic cone has led to significant shoreline mobility and is responsible for a 10 m submergence of the Roman harbor complexes (Dvorak and Mastrolorenzo, 1991). The pattern of movement inside the bay is spatially contrasted because around the fringes of the caldera the columns of the Roman market attest to an upper limit of marine bioerosion at 7 m above present sea level. Recent research suggests a series of post-Roman inflation-deflation cycles at both Pozzuoli (Morhange et al., 2006a) and Miseno (Cinque et al., 1991) linked to the interplay of deep magma inputs, fluid exsolution, and degassing (Todesco et al., 2004), all acting as drivers of rapid coastal change. Other studied examples of drowned cities include Helike and Kenchreai in the Gulf of Corinth, Greece (Kiskyras, 1988; Soter, 1998; Soter and Katsonopoulou, 1998; Rothaus et al., 2008) and Megisti on the island of Castellorizo, Greece (Pirazzoli, 1987).

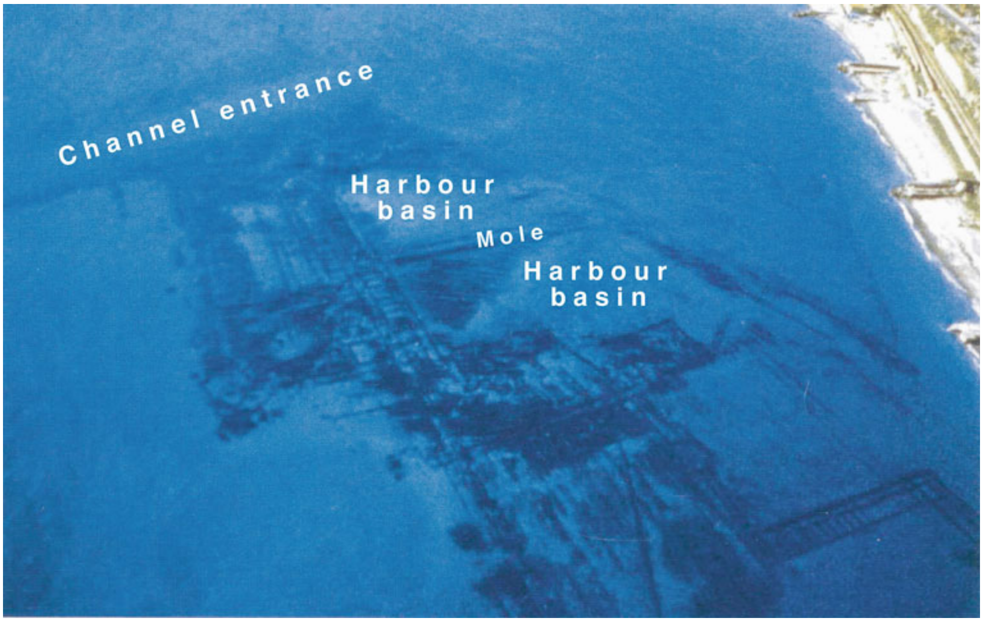
Uplifted harbors

The best geoarchaeological evidence for uplifted harbors derives from the Hellenic arc, one of the most seismically active regions in the world (Stiros, 2005).

In western Crete, Pirazzoli et al. (1992) have ascribed a 9 m uplift of Phalasarna harbor, founded in the fourth century BC, to high seismic activity in the eastern Mediterranean between the fourth to sixth centuries AD (Stiros, 2001). This episode is concurrent with a phase of Hellenic arc plate adjustment linked to uplift (1–2 m) in Turkey, e.g., the uplifted harbor of Seleucia Pieria (Pirazzoli et al., 1991), Syria (Sanlaville et al., 1997), and parts of the Lebanese coastline (Pirazzoli, 2005; Morhange et al., 2006b). Phalasarna's ancient harbor sediment record is of particular interest because its rapid uplift has possibly trapped tsunami deposits inside the basin (Dominey-Howes et al., 1998).

The Gulf of Corinth constitutes a neotectonic graben separating the Peloponnese from mainland Greece (Moretti et al., 2003; Evelpidou et al., 2011). It is one of the most tectonically active and rapidly extending regions in the world (6–15 mm/year) with a marked regional contrast between its subsiding northern coast and an uplifting southern flank borne out by its geomorphological features and archaeology (Papadopoulos et al., 2000; Koukouvelas et al., 2001). Biological and archaeological proxies attest to pronounced spatial disparities in the amplitude of uplift. The position of the gulf's ancient harbors can help to refine the recent tectonic history. The harbor of Heraion on the gulf's northern coast is, for instance, modestly uplifted by around 1 m (Pirazzoli et al., 1994).

The western harbor of Corinth at Lechaion is also uplifted. Emerged *Balanus* fossils indicating a former



Harbors and Ports, Ancient, Figure 7 Pozzuoli's drowned harbor remains presently ~10 m below mean sea level. The site lies inside a caldera, where shoreline mobility is attributed to volcanism and faulting (Photograph: Centre Jean Bérard, Naples).

biological sea level 1.2 m above the basin surface have been dated to around 2470 ± 45 BP, i.e., 375 ± 120 cal BC (Stiros et al., 1996). The location of the port basin in a well-protected depression suggests silting was already a problem during its excavation and not favorable to the basin's long-term viability as a seaport (Morhange et al., 2012). At Aigeira, an artificial Roman harbor was functional between ~100 AD and 250 AD (Papageorgiou et al., 1993). Biological and radiometric evidence from the city's harbor structures attests to ~4 m of uplift tentatively attributed to an earthquake around 250 AD (Stiros, 1998; Stiros, 2005).

In a different geodynamic context, Holocene evolution of Etna's coastline is associated with subduction of the African plate under the Eurasian plate. It presents a number of uplifted harbors, such as the neoria of the military harbor of Giardini-Naxos (Blackman and Lentini, 2010). This category of harbor is often poorly represented due to destruction by modern urbanization, e.g., the harbor of Kissamos, northwestern coast of Crete (Stefanakis, 2010).

Landlocked harbors

Around 6000 cal BP, the maximum marine ingression created an indented coastal morphology throughout the Mediterranean. During the ensuing millennia, these indented coastlines were gradually infilled by fluvial sediments reworked by longshore currents, culminating in a regularized coastal morphology. This process was particularly intense at deltaic margins.

Coastal progradation as a driver of settlement and harbor changes is best represented by Ionia's ancient ports in Turkey (Brückner, 1997), many of which are located inside infilled ria systems. Such rapid coastal change is linked to two factors: (1) broad sea-level stability since 6000 cal BP; and (2) the morphology of these paleovalleys, which correspond to narrow, transgressed grabens with limited accommodation space (Kayan, 1996; Kayan, 1999). For example, the Menderes floodplain has prograded by ~60 km during the past 7,000 years (Schröder and Bay, 1996). The best-studied examples include Troy (Kraft et al., 2003), where the harbor areas were landlocked by 2000 cal BP, and also Ephesus, Priene, and Miletos in Turkey (Brückner et al., 2005; Kraft et al., 2007).

In Cyprus, Devillers (2008) has elucidated the infilling of the Gialia's coastal embayment. The sedimentary archives attest to an easterly migration of the coastline. Human societies constantly adapted to this changing coastal environment as illustrated by the geographical shift of at least four ancient harbors: Early/Middle Bronze Age Kalopsidha, Middle/Late Bronze Age Enkomi, Graeco-Roman Salamina, and Medieval Famagusta. The latter is located on a rocky coast outside the paleo-ria.

Despite the ecological attraction of estuaries and fluvial mouths for harbor location, ancient engineers were aware of the longer-term hazards to survival. Greek settlers, for instance, founded Marseille around 600 BC at the distal margin of the Rhone delta in order to avoid the problems of rapid siltation. It is only in instances of absolute necessity that artificial ports were located inside deltaic systems. The Imperial harbors of Portus on the Tiber delta are a classic example (Goiran et al., 2010).

Eroded harbors

Eroded harbors can result from two complementary geological processes: (1) a fall in sediment supply to the coastal zone and/or (2) the destruction of harbor works in areas exposed to high-energy coastal processes. The best examples of eroded harbors date from the Roman period, when natural low-energy roadsteads were no longer a prerequisite for harbor location. At many high- to medium-energy coastal sites across the Mediterranean, the Romans constructed large enveloping moles to accommodate mooring facilities and interface installations such as fishponds and industrial saltpans. Good examples of eroded ancient harbors include Carthage and the outer Roman basin of Caesarea Maritima (Raban, 2009).

Fluvial harbors

River harbors are not subject to the same geomorphological and sedimentary processes as coastal seaports, and therefore diagnostic harbor sediment signatures can be markedly different. Unfortunately, geoarchaeological study of such contexts has been relatively limited until now. It is nonetheless an interesting avenue for future research and provides opportunities with which to compare and contrast the coastal data (Milne and Hobley, 1981; Good, 1991; de Izarra, 1993; Bravard and Magny, 2002; Arnaud-Fassetta et al., 2003). In particular, current research has focused upon the relationships between fluvial settlements, including their harbors, and flood hazards (Arnaud-Fassetta et al., 2003).

The environmental challenges of fluvial harbors are linked to: (1) seasonal and exceptional flood episodes (Stewart and Morhange, 2009); (2) river mouth access and rapidly shifting longshore bar development; and (3) the lateral instability of riverbanks (Bruneton et al., 2001; Brown, 2008).

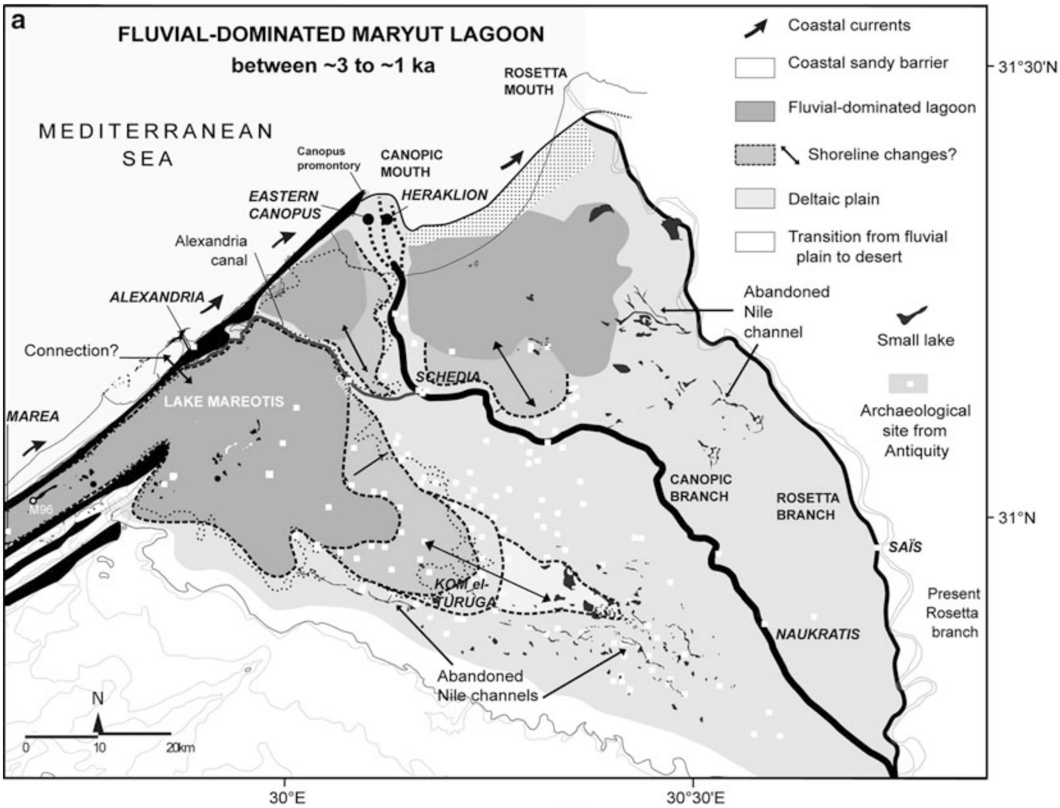
The Egyptians and Mesopotamians were among the earliest western civilizations to engage in fluvial transportation, and primeval Bronze Age harbor works are known from the banks of the Nile at Memphis and Giza (Fabre, 2004–2005). Despite excavations at a number of sites on the Nile Delta, e.g., Tell El-Daba/Avaris and Tell el-Fara'in (Bietak, 1996; Shaw, 2000), the exact location of many of the river ports is equivocal. There has been extensive research looking at the Canopic branch of the Nile Delta coast (Stanley and Jorstad, 2006; Stanley, 2007). Geoarchaeological data show that the Ptolemaic and Roman city of Schedia (Egypt) once lay directly on the Canopic channel, which was active from the third to second centuries BC until the fifth century AD. Abandonment of the site resulted from the avulsion of Nile waters to the Bolbitic and later Rosetta branches in the east. The discovery of a series of active and abandoned channels around the Greek city of Naukratis (Egypt) attests to significant fluvial mobility during antiquity. These channels served as transport pathways for the ancient settlement, although the site's fluvial port has never been precisely located (Villas, 1996). In the northeastern part of the Nile Delta, a number of sites on the now-defunct Pelusiac branch (Sneh and Weissbrod, 1973) have attracted geoarchaeological interest. Goodfriend and Stanley (1999) have shown that Pelusium, an important fortified city located at the mouth of the Pelusiac branch, was abandoned during the twelfth century AD following a large and rapid influx of Nile river sediment in the ninth century AD. This discharge in sediment led to the avulsion of a new distributory to the west, probably the Damietta branch.

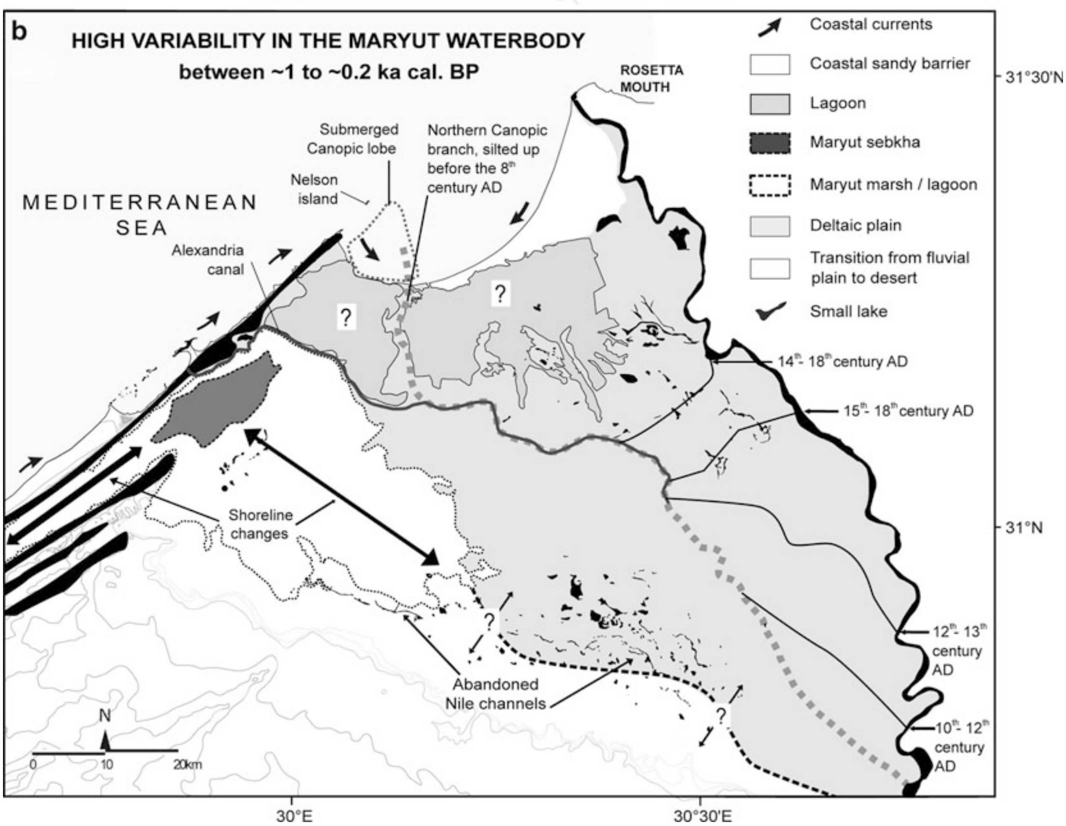
Aquileia in northeastern Italy is a well-studied example of a Roman fluvial harbor. A series of important waterways characterized the Aquileia deltaic plain during antiquity. These were channelized during the Roman period so as to ensure favorable conditions for navigation and to mitigate against the impact of floods (Arnaud-Fassetta et al., 2003). A similar evolution is attested at Minturnae (Italy), which controlled the bridge on the Appian Way over the Liris River. It occupied a prime location that allowed the Roman colony to evolve into a flourishing commercial center until its final abandonment around 590 AD. Recent geoarchaeological work undertaken at the mouth of the Tiber delta, around the ancient site of Ostia, has probed the evolution of the city's ancient harbor, which serviced ancient Rome around 32 km upriver (Goiran et al., 2012). Problems of basin silting meant that the harbor had already experienced an important phase of sediment infilling by the first century AD (Goiran et al., 2014). Continued late Holocene progradation dynamics have isolated ancient Ostia, which is now about 4 km from the present coastline. The silting of the harbor basin probably acted as a precursor to the construction of Rome's new port basin at Portus, although Ostia and the fluvial banks of the Tiber continued to accommodate smaller, shallow-draft vessels.

At a number of sites, the excavation of ancient harbor quays has facilitated the precise reconstruction of fluvial bank mobility since antiquity. This can be linked to the vertical accretion of riverbanks by flooding and the gradual funneling of fluvial waters by human activities. In London, for instance, Milne (1985) has described a 100 m shift in the port's waterfront between AD 100 and today. Under a mesotidal fluvial regime, funneling of the waterbody has led to a positive increase in tidal amplitude. A similar evolution is also attested at Bordeaux (France), where the staircasing of numerous quays and platforms has been described at two sites in the Garonne estuary (Gé et al., 2005). Three ancient and medieval platforms attest to a positive change in tidal amplitude of around 1.1 m during the twelfth to fourteenth centuries AD that can probably be linked to human impacts on the fluvial system.

Lagoonal harbors

Since 6000 BP, spit accretion on clastic coasts has disconnected a number of paleo-bays from the open sea. This process formed lagoons that have gradually infilled to yield rich geological archives. Lagoons offer natural protection,





Harbors and Ports, Ancient, Figure 8 (Continued) and their use as anchorage havens has been widespread since early antiquity. Nevertheless, lagoons pose a number of challenges that explain why these contexts were largely avoided as harbors during later periods: (1) difficult accessibility, namely, the mobility of the outlet channel that was particularly problematic for navigation, and (2) seasonal fluctuations in lagoon level, especially in the case of large waterbodies at the margins of fluvial systems.

Maryut lagoon lies at the northwestern margin of the Nile Delta, in a depression between two consolidated sandstone ridges of Pleistocene age (Flaux et al., 2011; Figure 8). The lagoon presently extends for 70 km on a - SW-NE axis with a maximum width of ~10 km. During antiquity, Nile inflow into the Maryut was supplied by the Canopic, the westernmost branch of the Nile. The Maryut's location at the intersection between the Mediterranean Sea and a major fluvial system has driven important paleoenvironmental changes during the past 8,000 years (Flaux, 2012; Flaux et al., 2012; Flaux et al., 2013). It is also responsible for significant seasonal variations in lagoon levels, driven by annual Nile flood cycles. There has been renewed interest in the Maryut because mounting archaeological evidence suggests that the lagoon was an important waterway during antiquity, with a densely occupied shoreline and numerous harbors and mooring sites (Blue and Khalil, 2010). Recent work by Flaux (2012) has demonstrated that the lagoon's Hellenistic and Roman harbors present a steplike mooring architecture to accommodate these seasonal fluctuations. Similar annual variations of around 1.4 m are also attested in the Dead Sea and the Sea of Galilee (Hadas, 2011). Reinforced landing quays at the Roman harbor of Magdala (Israel) comprise a comparable architecture to offset such variation and avoid erosional undercutting (De Luca, 2009). Recent work has unearthed a well-preserved harbor structure, extending for more than 100 m, which was functional during the Hellenistic and Roman periods (Sarti et al., 2013). Chronostratigraphic investigations have demonstrated that the harbor basin silted up and was abandoned during the Middle to Late Roman period (270–350 AD).

Lagoonal systems were particularly conducive to endo-lagoonal harbor circulation. A number of lagoon strings were exploited in the Mediterranean during Roman times, most famously the Fossa Neronis (Italy) in the direction of Rome (Cuma, Campania), Narbonne in southern France (Sanchez and Jézégou, 2011), and the upper Adriatic lagoons between Istria and the Po (Degrassi, 1955). New archaeological data from the Maryut lagoon in Egypt also suggest that the basin possessed a series of harbor complexes and mooring sites during Hellenistic and Roman times (Blue and Khalil, 2010). At present, the archetype of a harbor lagoon is medieval Venice which operated very successfully as a port up until recent modification of its marginal marine system.

Conclusions and future research directions

The impact of ancient harbor geoarchaeology on our understanding of the archaeological record in waterfront areas is clear and explicit. We have presented methods for reconstructing ancient harbor landscapes at a wide range of temporal and spatial scales, drawing on geoscience techniques, paleoecology and archaeology. With particular emphasis on the Mediterranean region, we have concentrated on the description and illustration of selected case study examples drawn from different geomorphological contexts. These lay the foundations for more geographically extensive studies, integrating the archaeological record with sediment archives for many Holocene time periods.

Some of the main advances made during the past 20 years include (1) the precise characterization of harbor facies in coastal contexts, using a variety of sedimentological, geochemical, and paleoecological proxies; (2) the characterization and intensity of human impacts in coastal areas (e.g., Véron et al., 2006); and (3) the scope to derive high-resolution RSL data (e.g., Morhange et al., 2001). Ancient harbor research is a rapidly evolving offshoot of geoarchaeology, and there is reason to be optimistic about its future prospects and applications. For the Mediterranean, as geographical gaps are gradually being filled and new research methods developed, more finite, regional-scale interpretations are becoming possible at a variety of temporal scales.

Current gaps in knowledge relate to the chronostratigraphic characterization of harbor facies in fluvial contexts that, in the absence of archaeological structures, renders the precise localization of harbor basins particularly challenging. Furthermore, our understanding of ancient harbor geoarchaeology is biased towards later periods, particularly Greek and Roman ports. Major gaps remain with regard to the Bronze Age, and future studies must look to probe these earlier periods. While our understanding of Mediterranean harbors continues to improve, it seems important to extend research to new geographical regions such as China, the Red Sea, and the Persian Gulf. One area of concern is the rise in catastrophic research in harbor contexts that mirrors the growth of neocatastrophic research during the past 20 years (Marriner et al., 2010; Marriner and Morhange, 2013). We advocate for the adoption of more nuanced approaches to the study of high-energy episodic events such as tsunamis and earthquakes.

Harbors and Ports, Ancient, Figure 8 Evolution of the Maryut lagoon during the past 3,000 years (From Flaux, 2012). The general aridification trend described during this period appears to be linked to the gradual decline of the Canopic branch of the Nile, which supplied the Maryut lagoon with freshwater.

Bibliography

Abulafia, D., 2011. *The Great Sea: A Human History of the Mediterranean*. London: Allen Lane.

Arnaud, P., 2005. *Les routes de la navigation antique: Itinéraires en Méditerranée*. Paris: Editions Errance.

Arnaud-Fassetta, G., Carre, M.-B., Marocco, R., Maselli Scotti, F., Pugliese, N., Zaccaria, C., Bandelli, A., Bresson, V., Manzoni, G., Montenegro, M. E., Morhange, C., Pipan, M., Prizzon, A., and Siché, I., 2003. The site of Aquileia (northeastern Italy): example of fluvial geoarchaeology in a Mediterranean deltaic plain. *Géomorphologie: relief, processus, environnement*, **9**(4), 227–245.

Bailey, G. N., and Flemming, N. C., 2008. Archaeology of the continental shelf: marine resources, submerged landscapes and underwater archaeology. *Quaternary Science Reviews*, **27** (23–24), 2153–2165.

Bard, K. A., and Fattovich, R., 2010. Recent excavations at the ancient harbor of Saww (Mersa/Wadi Gawasis) on the Red Sea. In D'Auria, S. H. (ed.), *Offerings to the Discerning Eye*. Brill: Leiden, pp. 33–38.

Bellotti, P., Mattei, M., Tortora, P., and Valeri, P., 2009. Geoarchaeological investigations in the area of the imperial harbours of Rome. *Méditerranée*, **112**, 51–58.

Bicket, A. R., Rendell, H. M., Claridge, A., Rose, P., Andrews, J., and Brown, F. S. J., 2009. A multiscale geoarchaeological approach from the Laurentine shore (Castelporziano, Lazio, Italy). *Géomorphologie: relief, processus, environnement*, **2009**(4), 241–256.

Bietak, M., 1996. *Avaris, the Capital of the Hyksos: Recent Excavations at Tell el-Dab'a*. London: British Museum Press.

Bini, M., Chelli, A., Durante, A. M., Gervasini, L., and Pappalardo, M., 2009. Geoarchaeological sea-level proxies from a silted up harbour: a case study of the Roman colony of Luni (northern Tyrrhenian Sea, Italy). *Quaternary International*, **206**(1–2), 147–157.

Blackman, D. J., 1982a. Ancient harbours in the Mediterranean, Part 1. *International Journal of Nautical Archaeology and Underwater Exploration*, **11**(2), 79–104.

Blackman, D. J., 1982b. Ancient harbours in the Mediterranean, Part 2. *International Journal of Nautical Archaeology and Underwater Exploration*, **11**(3), 185–211.

Blackman, D. J., and Lentini, M. C. (eds.), 2010. *Ricoveri per navi militari nei porti del Mediterraneo antico e medievale*. Bari: Edipuglia.

Blue, L. K., and Khalil, E. (eds.), 2010. *Lake Mareotis: Reconstructing the Past*. Oxford: Archaeopress. British Archaeological Reports International Series, Vol. 2113.

Boetto, G., 2012. Les épaves comme sources pour l'étude de la navigation et des routes commerciales: une approche méthodologique. In Keay, S. J. (ed.), *Rome, Portus and the Mediterranean*. Rome: British School at Rome. Archaeological Monographs, Vol. 21, pp. 153–173.

Bony, G., 2013. Contraintes et potentialités naturelles de quelques sites portuaires antiques de Méditerranée et de Mer Noire (Fréjus, Ampurias, Kition, Istanbul, Orgame). PhD thesis, Aix-en-Provence, Aix-Marseille Université.

Bony, G., Marriner, N., Morhange, C., Kaniewski, D., and Perinçek, D., 2012. A high-energy deposit in the Byzantine harbour of Yenikapı, Istanbul (Turkey). *Quaternary International*, **266**, 117–130.

Bottari, C., and Carveni, P., 2009. Archaeological and historiographical implications of recent uplift of the Peloro Peninsula, NE Sicily. *Quaternary Research*, **72**(1), 38–46.

Boyce, J. I., Reinhardt, E. G., and Goodman, B. N., 2009. Magnetic detection of ship ballast deposits and anchorage sites in King Herod's Roman harbour, Caesarea Maritima, Israel. *Journal of Archaeological Science*, **36**(7), 1516–1526.

Braidwood, R. J., 1940. Report on two sondages on the coast of Syria, south of Tartous. *Syria*, **21**(2), 183–226.

Brandon, C., Hohlfelder, R. L., Oleson, J. P., and Stern, C., 2005. The Roman Maritime Concrete Study (ROMACONS): the harbour of Chersonisos in Crete and its Italian connection. *Méditerranée*, **104**, 25–29.

Brandon, C., Hohlfelder, R. L., Oleson, J. P., and Rauh, N., 2010. Geology, materials, and the design of the Roman harbour of Soli-Pompeiopolis, Turkey: the ROMACONS field campaign of August 2009. *International Journal of Nautical Archaeology*, **39**(2), 390–399.

Braudel, F., 2002. *The Mediterranean in the Ancient World*. London: Penguin.

Bravard, J.-P., and Magny, M. (eds.), 2002. *Les fleuves ont une histoire: paléo-environnement des rivières et des lacs français depuis 15000 ans*. Paris: Editions Errance.

Brown, A. G., 2008. Geoarchaeology, the four dimensional (4D) fluvial matrix and climatic causality. *Geomorphology*, **101**(1–2), 278–297.

Brückner, H., 1997. Coastal changes in western Turkey; rapid delta progradation in historical times. In Briand, F., and Maldonado, A. (eds.), *Transformations and Evolution of the Mediterranean Coastline*. Monaco: Musée océanographique. Monaco, Bulletin de l'Institut océanographique, Special volume 18, pp. 63–74.

Brückner, H., Müllenhoff, M., van der Borg, K., and Vött, A., 2004. Holocene coastal evolution of western Anatolia – the interplay between natural factors and human impact. In CIESM (Commission Internationale pour l'Exploration Scientifique de la mer Méditerranée) (ed.), *Human Records of Recent Geological Evolution in the Mediterranean Basin – Historical and Archaeological Evidence (Santorini, Greece, 22–25 October 2003)*. Monaco: CIESM Workshop Monographs 24, pp. 51–56.

Brückner, H., Vött, A., Schriever, M., and Handl, M., 2005. Holocene delta progradation in the eastern Mediterranean – case studies in their historical context. *Méditerranée*, **104**, 95–106.

Bruneton, H., Arnaud-Fassetta, G., Provansal, M., and Sistach, D., 2001. Geomorphological evidence for fluvial change during the Roman period in the lower Rhone valley (southern France). *CATENA*, **45**(4), 287–312.

Butzer, K. W., 1982. *Archaeology as Human Ecology: Method and Theory for a Contextual Approach*. Cambridge: Cambridge University Press.

Butzer, K. W., 2005. Environmental history in the Mediterranean world: cross-disciplinary investigation of cause-and-effect for degradation and soil erosion. *Journal of Archaeological Science*, **32**(12), 1773–1800.

Butzer, K. W., 2008. Challenges for a cross-disciplinary geoarchaeology: the intersection between environmental history and geomorphology. *Geomorphology*, **101**(1–2), 402–411.

Butzer, K. W., Butzer, E., and Love, S., 2013. Urban geoarchaeology and environmental history at the Lost City of the Pyramids, Giza: synthesis and review. *Journal of Archaeological Science*, **40**(8), 3340–3366.

Buynevich, I. V., Yanko-Hombach, V., Gilbert, A. S., and Martin, R. E. (eds.), 2011. *Geology and Geoarchaeology of the Black Sea Region: Beyond the Flood Hypothesis*. Boulder: Geological Society of America Special Paper 473.

Carayon, N., 2005. Le *cothon* ou port artificiel creusé. *Essai de définition. Méditerranée*, **104**, 5–13.

Carayon, N., 2008. *Les ports phéniciens et puniques: géomorphologie et infrastructures*. PhD thesis, Strasbourg, Université Marc Bloch – Strasbourg II.

Carsana, V., Febbraro, S., Giampaola, D., Guastaferro, C., Irollo, G., and Ruello, M. R., 2009. Evoluzione del paesaggio costiero tra *Parthenope* e *Neapolis*. *Méditerranée*, **112**, 14–22.

Casson, L., 1994. *Travel in the Ancient World*. Baltimore: Johns Hopkins University Press.

Chen, Z., Zong, Y., Wang, Z., Wang, H., and Chen, J., 2008. Migration patterns of Neolithic settlements on the abandoned Yellow and Yangtze River deltas of China. *Quaternary Research*, **70**(2), 301–314.

Chittick, N., 1979. Early ports in the Horn of Africa. *International Journal of Nautical Archaeology*, **8**(4), 273–277.

Cinque, A., Russo, F., and Pagano, M., 1991. La successione dei terreni di età post-Romana delle terme di Miseno (Napoli): nuovi dati per la storia e la stratigrafia del bradisisma puteolano. *Bolletino della Società Geologica Italiana*, **110**(2), 231–244.

Coles, B., and Coles, J. M., 1989. *People of the Wetlands: Bogs Bodies and Lake-dwellers*. London: Thames and Hudson.

Coles, J. M., and Lawson, A. J. (eds.), 1987. *European Wetlands in Prehistory*. Oxford: Clarendon.

Collina-Girard, J., 2001. L'Atlantide devant le détroit de Gibraltar? *Mythe et géologie. Comptes Rendus de l'Académie des Sciences. Sciences de la Terre et des planètes*, **333**(4), 233–240.

de Izarra, F., 1993. *Le fleuve et les hommes en Gaule romaine*. Paris: Errance.

De Luca, S., 2009. La città ellenistico-romana di Magdala/Taricheae. Gli scavi del Magdala project 2007 e 2008: relazione preliminare e prospettive di indagine. *Liber Annuus*, **59**, 343–562.

Degrassi, A., 1955. I porti romani dell'Istria. In Fiocco, G. (ed.), *Anthemon, Scritti di Archeologia e di Antichità Classiche in onore di Carlo Anti*. Florence: G. C. Sansoni, pp. 119–169.

Devillers, B., 2008. *Holocene Morphogenesis and Anthropisation of a Semi-Arid Watershed, Gialias River, Cyprus*. Oxford: Archaeopress. British Archaeological Reports International Series, Vol. 1775.

Di Bella, L., Bellotti, P., Frezza, V., Bergamin, L., and Carboni, M. G., 2011. Benthic foraminiferal assemblages of the imperial harbor of Claudius (Rome): further paleoenvironmental and geoarcheological evidences. *The Holocene*, **21**(8), 1245–1259.

Dominey-Howes, D., Dawson, A., and Smith, D., 1998. Late Holocene coastal tectonics at Falasarna, western Crete: a sedimentary study. In Stewart, I. S., and Vita-Finzi, C. (eds.), *Coastal Tectonics*. London: Geological Society. Special Publication, Vol. 146, pp. 343–352.

Dvorak, J. J., and Mastrolorenzo, G., 1991. *The Mechanisms of Recent Vertical Crustal Movements in Campi Flegrei Caldera, Southern Italy*. Boulder: Geological Society of America. Special Paper, Vol. 263.

Empereur, J.-Y., and Grimal, N., 1997. Les fouilles sous-marines du phare d'Alexandrie. *Compte-rendus de l'Académie des Inscriptions et Belles-Lettres*, **141**(3), 693–717.

Empereur, J.-Y., and Verlinden, C., 1987. The underwater excavations at the Ancient port of Amathus in Cyprus. *International Journal of Nautical Archaeology*, **16**(1), 7–18.

Evelpidou, N., Pirazzoli, P. A., Saliège, J.-F., and Vassilopoulos, A., 2011. Submerged notches and doline sediments as evidence for Holocene subsidence. *Continental Shelf Research*, **31**(12), 1273–1281.

Fabre, D., 2004–2005. *Seafaring in Ancient Egypt*. London: Periplus.

Flaux, C., 2012. Holocene Palaeo-environments of the Maryut Lagoon in the NW Nile Delta, Egypt. PhD thesis, Aix-en-Provence, Aix-Marseille Université.

Flaux, C., Morhange, C., Marriner, N., and Rouchy, J.-M., 2011. Bilan hydrologique et biosédimentaire de la lagune du Maryût (delta du Nil, Egypte) entre 8 000 et 3 200 ans cal. B.P. *Gé omorphologie*, **2011**(3), 261–278.

Flaux, C., El-Assal, M., Marriner, N., Morhange, C., Rouchy, J.-M., Soulié-Märsche, I., and Torab, M., 2012. Environmental changes in the Maryut lagoon (northwestern Nile delta) during the last ~2000 years. *Journal of Archaeological Science*, **39**(12), 3493–3504.

Flaux, C., Claude, C., Marriner, N., and Morhange, C., 2013. A 7500-year strontium isotope record from the northwestern Nile delta (Maryut lagoon, Egypt). *Quaternary Science Reviews*, **78**, 22–33.

Flemming, N. C., 1971. *Cities in the Sea*. Garden City, NY: Doubleday.

Frost, H., 1963. *Under the Mediterranean*. London: Routledge and Kegan Paul.

Frost, H., 1964. Rouad, ses récifs et mouillages. Prospection sous-marine. *Annales Archéologiques de Syrie*, **14**, 67–74.

Frost, H., 1973. The offshore island harbour at Sidon and other Phoenician sites in the light of new dating evidence. *The International Journal of Nautical Archaeology and Underwater Exploration*, **2**(1), 75–94.

Galili, E., Weinstein-Evron, M., and Ronen, A., 1988. Holocene sea-level changes based on submerged archaeological sites off the northern Carmel coast in Israel. *Quaternary Research*, **29**(1), 36–42.

Gambin, T., 2004. Islands of the Middle Sea: an archaeology of a coastline. In De Maria, L., and Turchetti, R. (eds.), *Evolución paleoambiental de los puertos y fondeaderos antiguos en el Mediterráneo occidental*. Soveria Mannelli: Rubbettino Editore, pp. 127–146.

Gambin, T., 2005. The Maritime Landscapes of Malta from the Roman Period to the Middle Ages. PhD thesis, University of Bristol.

Gaur, A. S., 2000. *Harappan Maritime Legacies of Gujarat*. New Delhi: Asian Publication Services.

Gaur, A. S., and Vora, K. H., 1999. Ancient shorelines of Gujarat, India, during the Indus civilization (Late Mid-Holocene): a study based on archaeological evidences. *Current Science*, **77**(1), 180–185.

Gazda, E. K., 2001. Cosa's contribution to the study of Roman hydraulic concrete: an historiographic commentary. In Goldman, N. W. (ed.), *New Light from Ancient Cosa: Classical Mediterranean Studies in Honor of Cleo Rickman Fitch*. New York: American Academy in Rome/Peter Lang, pp. 145–177.

Gé, T., Migeon, W., and Szepertyski, B., 2005. L'élévation séculaire des berges antiques et médiévales de Bordeaux. Étude géoarchéologique et dendrochronologique. *Comptes Rendus Geoscience*, **337**(3), 297–303.

Gébara, C., and Morhange, C., 2010. Fréjus (Forum Julii): le port antique/The Ancient Harbour. *Journal of Roman Archaeology*, Supplementary Series Number 77, 1–152.

Ghilardi, M., and Desruelles, S., 2009. Geoarchaeology: where human, social and earth sciences meet with technology. *S.A.P.I. EN.S*, 2(2): http://sapiens.revues.org/422.

Giampaola, D., Carsana, V., and Boetto, G., 2004. Il mare torna a bagnare Neapolis. Parte II: dalla scoperta del porto al recupero dei relitti. *L'Archeologo Subacqueo*, **10**(3), 15–19.

Gianfrotta, P. A., 1996. Harbor structures of the Augustan Age in Italy. In Raban, A., and Holum, K. G. (eds.), *Caesarea Maritima: A Retrospective After Two Millennia*. Leiden: Brill Academic Publishers. Documenta et Monumenta Orientis Antiqui, Vol. 21, pp. 65–76.

Giraudi, C., Tata, C., and Paroli, L., 2009. Late Holocene evolution of Tiber river delta and geoarchaeology of Claudius and Trajan Harbor, Rome. *Geoarchaeology*, **24**(3), 371–382.

Goddio, F., Bernand, A., Bernand, E., Darwish, I., Kiss, Z., and Yoyotte, J., 1998. *Alexandria: The Submerged Royal Quarters*. London: Periplus.

Goiran, J.-P., 2001. Recherches géomorphologiques dans la region littorale d'Alexandrie, Egypte. PhD thesis, Aix-en-Provence, Université de Provence.

Goiran, J. P., Tronchère, H., Salomon, F., Carbonel, P., Djerbi, H., and Ognard, C., 2010. Palaeoenvironmental reconstruction of the ancient harbors of Rome: Claudius and Trajan's marine harbors on the Tiber delta. *Quaternary International*, **216**(1), 3–13.

Goiran, J.-P., Pavlopoulos, K. P., Fouache, E., Triantaphyllou, M., and Etienne, R., 2011. Piraeus, the ancient island of Athens; evidence from Holocene sediments and historical archives. *Geology*, **39**(6), 531–534.

Goiran, J.-P., Salomon, F., Pleuger, E., Vittori, C., Mazzini, I., Boetto, G., Arnaud, P., and Pellegrino, A., 2012. Résultats préliminaires de la première campagne de carottages dans le port antique d'Ostie. *Chroniques des Mélanges de l'Ecole Française de Rome*, **123**(2), 2–7.

Goiran, J.-P., Salomon, F., Mazzini, I., Bravard, J.-P., Pleuger, E., Vittori, C., Boetto, G., Christiansen, J., Arnaud, P., Pellegrino, A., Pepe, C., and Sadori, L., 2014. Geoarchaeology confirms location of the ancient harbour basin of Ostia (Italy). *Journal of Archaeological Science*, **41**, 389–398.

Good, G. L. (ed.), 1991. *Waterfront Archaeology: Proceedings of the Third International Conference on Waterfront Archaeology held at Bristol, 23–26 September 1988*. York: Council for British Archaeology.

Goodfriend, G. A., and Stanley, J.-D., 1999. Rapid strand-plain accretion in the northeastern Nile Delta in the 9th century A. D. and the demise of the port of Pelusium. *Geology*, **27**(2), 147–150.

Guidoboni, E., Comastri, A., and Traina, G., 1994. *Catalogue of Ancient Earthquakes in the Mediterranean Area up to the 10th Century*. Roma: Istituto Nazionale di Geofisica.

Gutscher, M.-A., 2005. Destruction of Atlantis by a great earthquake and tsunami? A geological analysis of the Spartel Bank hypothesis. *Geology*, **33**(8), 685–688.

Hadas, G., 2011. Dead Sea anchorages. *Revue biblique*, **118**(2), 161–179.

Haggi, A., 2006. Phoenician Atlit and its newly-excavated harbour: a reassessment. *Tel Aviv: Journal of the Institute of Archaeology of Tel Aviv University*, **33**(1), 43–60.

Haggi, A., and Artzy, M., 2007. The harbor of Atlit in northern Canaanite/Phoenician context. *Near Eastern Archaeology*, **70**(2), 75–84.

Halliday Saville, L., 1941. Ancient harbours. *Antiquity*, **15**(59), 209–232.

Hein, C. J., FitzGerald, D. M., Milne, G. A., Bard, K., and Fattovich, R., 2011. Evolution of a Pharaonic harbor on the Red Sea: implications for coastal response to changes in sea level and climate. *Geology*, **39**(7), 687–690.

Hesnard, A., 1994. Une nouvelle fouille du port de Marseille, Place Jules Verne. *Compte-rendus de l'Académie des Inscriptions et Belles-Lettres*, **138**(1), 195–216.

Hesnard, A., 1995. Les ports antiques de Marseille, Place Jules-Verne. *Journal of Roman Archaeology*, **8**, 65–77.

Hesnard, A., 2004. Terre submergée, mer enterrée: une « géoarchéologie » du port antique de Marseille. In De Maria, L., and Turchetti, R. (eds.), *Evolución paleoambiental de los puertos y fondeaderos antiguos en el Mediterráneo occidental*. Soveria Mannelli: Rubbettino Editore, pp. 3–29.

Hesse, A., 1998. Arguments pour une nouvelle hypothèse de localisation de l'Heptastade d'Alexandrie. In Empereur, J.-Y. (ed.), *Études Alexandrines 1*. Cairo: Institut Français d'Archéologie Orientale, pp. 21–33.

Hesse, A., 2000. Archaeological prospection. In Ellis, L. (ed.), *Archaeological Method and Theory: An Encyclopedia*. New York: Garland Publishing, pp. 33–39.

Heyvaert, V. M., and Baeteman, C., 2008. A middle to late Holocene avulsion history of the Euphrates river: a case study from Tell ed-Dēr, Iraq, Lower Mesopotamia. *Quaternary Science Reviews*, **27**(25–26), 2401–2410.

Hohlfelder, R. L., 1997. Building harbours in the early Byzantine era: the persistence of Roman technology. *Byzantische Forschungen*, **24**, 367–380.

Horden, P., and Purcell, N., 2000. *The Corrupting Sea: A Study of Mediterranean History*. Oxford: Blackwell Publishers.

Ilves, K., 2009. Discovering harbours? Reflection on the state and development of landing site studies in the Baltic Sea region. *Journal of Maritime Archaeology*, **4**, 149–163.

Jondet, G., 1916. *Les ports submergés de l'ancienne île de Pharos*. Cairo: l'Institut égyptien. Mémoire 9.

Kayan, I., 1996. Holocene coastal development and archaeology in Turkey. *Zeitschrift für Geomorphologie Supplementband*, **102**, 37–59.

Kayan, I., 1999. Holocene stratigraphy and geomorphological evolution of the Aegean coastal plains of Anatolia. *Quaternary Science Reviews*, **18**(4–5), 541–548.

Keay, S., and Paroli, L. (eds.), 2011. *Portus and its Hinterland: Recent Archaeological Research*. London: British School at Rome. Archaeological Monographs, Vol. 18.

Keay, S., Millett, M., Paroli, L., and Strutt, K. (eds.), 2005. *Portus: An Archaeological Survey of the Port of Imperial Rome*. London: British School at Rome. Archaeological Monographs, Vol. 15.

Keay, S., Earl, G., Hay, S., Kay, S., Ogden, J., and Strutt, K. D., 2009. The role of integrated geophysical survey methods in the assessment of archaeological landscapes: the case of Portus. *Archaeological Prospection*, **16**(3), 154–166.

Keller, F., 1866. *The Lake-Dwellings of Switzerland and Other Parts of Europe*. London: Longmans Green.

Khalil, E., 2010. The sea, the river and the lake: all the waterways lead to Alexandria. *Bollettino di Archeologia, volume speciale* B/B7/5, 33–48.

Kiskyras, D. A., 1988. The reasons for the disappearance of the ancient Greek town Helice (Eliki): geological contribution to the search for it. In Marinos, P. G., and Koukis, G. C. (eds.), *Engineering Geology of Ancient Works, Monuments and Historical Sites*. Rotterdam: Balkema, pp. 1301–1306.

Koukouvelas, I. K., Stamatopoulos, L., Katsonopoulou, D., and Pavlides, S., 2001. A palaeoseismological and geoarchaeological investigation of the Eliki fault, Gulf of Corinth, Greece. *Journal of Structural Geology*, **23**(2–3), 531–543.

Kraft, J. C., Rapp, G. R., Kayan, I., and Luce, J. V., 2003. Harbor areas at ancient Troy: sedimentology and geomorphology complement Homer's *Iliad. Geology*, **31**(2), 163–166.

Kraft, J. C., Brückner, H., Kayan, I., and Engelmann, H., 2007. The geographies of ancient Ephesus and the Artemision in Anatolia. *Geoarchaeology*, **22**(1), 121–149.

Kramer, S. N., 1964. The Indus civilization and Dilmun: the Sumerian paradise land. *Expedition*, **6**(3), 44–52.

Laborel, J., and Laborel-Deguen, F., 1994. Biological indicators of relative sea-level variations and of co-seismic displacements in the Mediterranean region. *Journal of Coastal Research*, **10**(2), 395–415.

Lambeck, K., Anzidei, M., Antonioli, F., Benini, A., and Esposito, A., 2004. Sea level in Roman time in the Central Mediterranean and implications for recent change. *Earth and Planetary Science Letters*, **224**(3–4), 563–575.

Lauffray, J., Sauneron, S., and Traunecker, C., 1975. La tribune du quai de Karnak et sa favissa. Compte rendu des fouilles menées en 1971-1972 (2e campagne). *Cahiers de Karnak*, **5**, 43–76.

Lehmann-Hartleben, K., 1923. *Die Antiken Hafenanlagen des Mittelmeeres: Beiträge zur Geschichte des Städtebaues im Altertum*. Leipzig: Dietrich.

Leung Tack, K. D., 1971–72. Étude d'un milieu pollué: le Vieux-Port de Marseille. Influence des conditions physiques et chimiques sur la physionomie du peuplement de quai. *Téthys*, **3**(4), 767–825.

Leveau, P., 2005. L'archéologie du paysage et l'antiquité classique. *Agri Centuriati*, **2**, 9–24.
Leveau, P., Trément, F., Walsh, K., and Barker, G. (eds.), 1999. *Environmental Reconstruction in Mediterranean Landscape Archaeology*. Oxford: Oxbow Books.
Marcus, E., 2002a. Early seafaring and maritime activity in the southern Levant from prehistory through the third millennium BCE. In Van den Brink, E. C. M., and Levy, T. E. (eds.), *Egypt and the Levant: Interrelations from the 4th Through the Early 3rd Millennium BCE*. London: Leicester University Press, pp. 403–417.
Marcus, E., 2002b. The southern Levant and maritime trade during the Middle Bronze IIa period. In Oren, E., and Ahituv, S. (eds.), *Aharon Kempinski Memorial Volume: Studies in Archaeology and Related Disciplines*. Beer Sheva: Ben-Gurion University of the Negev Press. Studies by the Department of Bible and Ancient Near East, Vol. 15, pp. 241–263.
Marinatos, S., 1960. Helice: a submerged town of Classical Greece. *Archaeology*, **13**, 186–193.
Markoe, G. E., 2000. *Peoples of the Past: Phoenicians*. Berkeley: University of California Press.
Marriner, N., 2009. *Géoarchéologie des ports antiques du Liban*. Paris: L'Harmattan.
Marriner, N., and Morhange, C., 2006a. Geoarchaeological evidence for dredging in Tyre's ancient harbour, Levant. *Quaternary Research*, **65**(1), 164–171.
Marriner, N., and Morhange, C., 2006b. The 'Ancient Harbour Parasequence': anthropogenic forcing of the stratigraphic highstand record. *Sedimentary Geology*, **186**(1–2), 13–17.
Marriner, N., and Morhange, C., 2007. Geoscience of ancient Mediterranean harbours. *Earth-Science Reviews*, **80**(3–4), 137–194.
Marriner, N., and Morhange, C., 2013. Data mining the intellectual revival of "catastrophic" Mother Nature. *Foundations of Science*, **18**(2), 245–257.
Marriner, N., Morhange, C., Boudagher-Fadel, M., Bourcier, M., and Carbonel, P., 2005. Geoarchaeology of Tyre's ancient northern harbour, Phoenicia. *Journal of Archaeological Science*, **32**(9), 1302–1327.
Marriner, N., Morhange, C., Doumet-Serhal, C., and Carbonel, P., 2006a. Geoscience rediscovers Phoenicia's buried harbors. *Geology*, **34**(1), 1–4.
Marriner, N., Morhange, C., and Doumet-Serhal, C., 2006b. Geoarchaeology of Sidon's ancient harbours, Phoenicia. *Journal of Archaeological Science*, **33**(11), 1514–1535.
Marriner, N., Morhange, C., and Carayon, N., 2008. Ancient Tyre and its harbours: 5000 years of human-environment interactions. *Journal of Archaeological Science*, **35**(5), 1281–1310.
Marriner, N., Morhange, C., and Skrimshire, S., 2010. Geoscience meets the four horsemen? Tracking the rise of neocatastrophism. *Global and Planetary Change*, **74**(1), 43–48.
Martini, I. P., and Chesworth, W. (eds.), 2010. *Landscapes and Societies*. Dordrecht: Springer.
Mason, O. K., 1993. The geoarchaeology of beach ridges and cheniers: studies of coastal evolution using archaeological data. *Journal of Coastal Research*, **9**(1), 126–146.
Mazzini, I., Faranda, C., Giardini, M., Giraudi, C., and Sadori, L., 2011. Late Holocene palaeoenvironmental evolution of the Roman harbour of Portus, Italy. *Journal of Paleolimnology*, **46**(2), 243–256.
Menotti, F., and O'Sullivan, A., 2012. *The Oxford Handbook of Wetland Archaeology*. Oxford: Oxford University Press.
Milne, G., 1985. *The Port of Roman London*. London: Batsford.
Milne, G., 2003. *The Port of Medieval London*. Stroud: Tempus.
Milne, G., and Hobley, B. (eds.), 1981. *Waterfront Archaeology in Britain and Northern Europe*. London: Council for British Archaeology.
Moretti, I., Sakellariou, D., Lykousis, V., and Micarelli, L., 2003. The Gulf of Corinth: an active half graben? *Journal of Geodynamics*, **36**(1–2), 323–340.
Morhange, C., and Marriner, N., 2010a. Mind the (stratigraphic) gap: Roman dredging in ancient Mediterranean harbours. *Bollettino di Archeologia, volume speciale* B/B7/4, 23–32.
Morhange, C., and Marriner, N., 2010b. Palaeo-hazards in the coastal Mediterranean: a geoarchaeological approach. In Martini, I. P., and Chesworth, W. (eds.), *Landscapes and Societies*. Dordrecht: Springer, pp. 223–234.
Morhange, C., Laborel, J., and Hesnard, A., 2001. Changes of relative sea level during the past 5000 years in the ancient harbor of Marseilles, Southern France. *Palaeogeography Palaeoclimatology Palaeoecology*, **166**(3–4), 319–329.
Morhange, C., Blanc, F., Schmitt-Mercury, S., Bourcier, M., Carbonel, P., Oberlin, C., Prone, A., Vivent, D., and Hesnard, A., 2003. Stratigraphy of late-Holocene deposits of the ancient harbour of Marseilles, southern France. *The Holocene*, **13**(4), 593–604.
Morhange, C., Hamdan Taha, M., Humbert, J.-B., and Marriner, N., 2005. Human settlement and coastal change in Gaza since the Bronze Age. *Méditerranée*, **104**, 75–78.
Morhange, C., Marriner, N., Laborel, J., Todesco, M., and Oberlin, C., 2006a. Rapid sea-level movements and noneruptive crustal deformations in the Phlegrean Fields caldera, Italy. *Geology*, **34**(2), 93–96.
Morhange, C., Pirazzoli, P. A., Marriner, N., Montaggioni, L. F., and Nammour, T., 2006b. Late Holocene relative sea-level changes in Lebanon, Eastern Mediterranean. *Marine Geology*, **230** (1–2), 99–114.
Morhange, C., Pirazzoli, P. A., Evelpidou, N., and Marriner, N., 2012. Tectonic uplift and silting up of Lechaion, the western harbour of ancient Corinth, Greece. *Geoarchaeology*, **27**(3), 278–283.
Morhange, C., Marriner, N., Excoffon, P., Bonnet, S., Flaux, C., Zibrowius, H., Goiran, J.-P., and El Amouri, M., 2013. Relative sea-level changes during Roman times in the northwest Mediterranean: the 1st century A.D. fish tank of Forum Julii, Fréjus, France. *Geoarchaeology*, **28**(4), 363–372.
Négris, P., 1904a. Vestiges antiques submergés. *Mitteilungen des Deutschen Archeologischen Instituts, Athenische Abteilung*, **29**, 340–363.
Négris, P., 1904b. Nouvelles observations sur la dernière transgression de la Méditerranée. *Comptes Rendus de l'Académie des Sciences*, **2**, 379–381.
Nishimura, Y., 2001. Geophysical prospection in archaeology. In Brothwell, D. R., and Pollard, A. M. (eds.), *Handbook of Archaeological Sciences*. Chichester: Wiley, pp. 543–553.
Oleson, J. P., 1988. The technology of Roman harbours. *International Journal of Nautical Archaeology*, **17**(2), 147–157.
Oleson, J. P., and Branton, G., 1992. The harbour of Caesarea Palaestinae: a case study of technology transfer in the Roman Empire. *Mitteilungen, Leichtweiß-Institut für Wasserbau*, **117**, 387–421.
Oleson, J. P., Brandon, C., Cramer, S. M., Cucitore, R., Gotti, E., and Hohlfelder, R. L., 2004. The ROMACONS Project: a contribution to the historical and engineering analysis of hydraulic concrete in Roman maritime structures. *International Journal of Nautical Archaeology*, **33**(2), 199–229.
Palley, R., 2010. *Concrete: A Seven-Thousand-Year History*. New York: Quantuck Lane Press.
Papadopoulos, G., Vassilopoulou, A., and Plessa, A., 2000. A new catalogue of historical earthquakes in the Corinth rift, central Greece: 480 BC-AD 1910. In Papadopoulos, G. (ed.), *Historical Earthquakes and Tsunamis in the Corinth Rift, Central Greece*.

Athens: National Observatory of Athens, Institute of Geodynamics, Vol. Publication 12, pp. 9–119.

Papageorgiou, S., Arnold, M., Laborel, J., and Stiros, S. C., 1993. Seismic uplift of the harbour of ancient Aigeira, Central Greece. *International Journal of Nautical Archaeology*, **22**(3), 275–281.

Paris, J., 1915. Contributions à l'étude des ports antiques du monde grec. I. Note sur Léchaion. *Bulletin de Correspondance Hellenique*, **39**, 5–16.

Paris, J., 1916. Contributions à l'étude des ports antiques du monde grec. II. Les établissements maritimes de Délos. *Bulletin de Correspondance Hellenique*, **40**, 5–73.

Pirazzoli, P. A., 1987. Submerged remains of ancient Megisti in Castellorizo Island (Greece): a preliminary survey. *International Journal of Nautical Archaeology*, **16**(1), 57–66.

Pirazzoli, P. A., 2005. A review of possible eustatic, isostatic and tectonic contributions in eight late-Holocene relative sea-level histories from the Mediterranean area. *Quaternary Science Reviews*, **24**(18–19), 1989–2001.

Pirazzoli, P., and Thommeret, J., 1973. Une donnée nouvelle sur le niveau marin à Marseille à l'époque romaine. *Comptes Rendus de l'Académie des Sciences*, **277**, 2125–2128.

Pirazzoli, P. A., Laborel, J., Saliège, J. F., Erol, O., Kayan, I., and Person, A., 1991. Holocene raised shorelines on the Hatay coasts (Turkey): palaeoecological and tectonic implications. *Marine Geology*, **96**(3–4), 295–311.

Pirazzoli, P. A., Ausseil-Badie, J., Giresse, P., Hadjidaki, E., and Arnold, M., 1992. Historical environmental changes at Phalasarna harbor, west Crete. *Geoarchaeology*, **7**(4), 371–392.

Pirazzoli, P. A., Stiros, S. C., Arnold, M., Laborel, J., Laborel-Deguen, F., and Papageorgiou, S., 1994. Episodic uplift deduced from Holocene shorelines in the Perachora Peninsula, Corinth area, Greece. *Tectonophysics*, **229**(3–4), 201–209.

Poidebard, A., 1939. *Un grand port disparu, Tyr; Recherches aé riennes et sous-marines 1934–1936*. Paris: Librairie Orientaliste Paul Geuthner.

Poidebard, A., and Lauffray, J., 1951. *Sidon, aménagements antiques du port de Saïda. Etude aérienne au sol et sous-marine, 1946–1950*. Beyrouth: Imprimerie Catholique.

Pomey, P., 1995. Les épaves grecques et romaines de la place Jules-Verne à Marseille. *Comptes Rendus de l'Académie des Inscriptions et Belles Lettres*, **139**(2), 459–484.

Pomey, P., and Rieth, E., 2005. *L'archéologie navale*. Paris: Editions Errance.

Pritchard, J. B., 1978. *Recovering Sarepta, a Phoenician City.* Princeton, NJ: Princeton University Press.

Puglisi, D., 2001. Un arsenale marittimo l'Edificio T di Kommòs? *Creta Antica*, **2**, 113–124.

Purdy, B. A. (ed.), 1988. *Wet Site Archaeology.* Caldwell, NJ: The Telford Press.

Raban, A., 1985. The Ancient Harbours of Israel in Biblical Times. In Raban, A. (ed.), *Harbour Archaeology; Proceedings of the First International Workshop on Ancient Mediterranean Harbours. Caesarea Maritima, 24–28.6.83. British Archaeological Reports International Series 257.* Oxford: British Archaeological Reports, pp. 11–44.

Raban, A., 1987. Alternated river courses during the Bronze Age along the Israeli coastline. In Euzennat, M., Paskoff, R., and Trousset, P. (eds.), *Déplacements des lignes de rivage en Mé diterranée d'après les données de l'archéologie*. Paris: CNRS, pp. 173–199.

Raban, A., 2009. *The Harbour of Sebastos (Caesarea Maritima) in its Roman Mediterranean Context.* Oxford: Archaeopress. British Archaeological Reports International Series 1930.

Raban, A., and Holum, K. G. (eds.), 1996. *Caesarea Maritima: A Retrospective after Two Millennia*. Leiden: Brill Academic Publishers.

Rao, S. R., 1979. *Lothal, a Harappan Port Town, 2 vols. Memoir 78*. New Delhi: Archaeological Survey of India.

Rao, S. R. (ed.), 1988. *Marine Archaeology of Indian Ocean Countries*. Goa: National Institute of Oceanography in Dona Paula.

Rao, S. R., 1991. *Dawn and Devolution of Indus Civilization*. New Delhi: Aditya Prakashan.

Ravilious, K., 2009. 'Biblical' flood created present-day Mediterranean. *The New Scientist*, **204**(2738), 12.

Reinhardt, E. G., and Raban, A., 1999. Destruction of Herod the Great's harbor at Caesarea Maritima, Israel – geoarchaeological evidence. *Geology*, **27**(9), 811–814.

Reinhardt, E. G., Patterson, R. T., and Schröder-Adams, C. J., 1994. Geoarchaeology of the ancient harbor site of Caesarea Maritima, Israel: evidence from sedimentology and paleoecology of benthic foraminifera. *Journal of Foraminiferal Research*, **24**(1), 37–48.

Reinhardt, E. G., Goodman, B. N., Boyce, J. I., Lopez, G., van Hengstum, P., Rink, W. J., Mart, Y., and Raban, A., 2006. The tsunami of 13 December A.D. 115 and the destruction of Herod the Great's harbor at Caesarea Maritima, Israel. *Geology*, **34**(12), 1061–1064.

Rickman, G. E., 1988. The archaeology and history of Roman ports. *International Journal of Nautical Archaeology*, **17**(3), 257–267.

Rosen, A. M., 1986. *Cities of Clay: The Geoarchaeology of Tells*. Chicago: The University of Chicago Press.

Rothaus, R., Reinhardt, E. G., and Noller, J. S., 2008. Earthquakes and subsidence at Kenchreai: using recent earthquakes to reconsider the archaeological and literary evidence. In Caraher, W. R., Hall, L. J., and Moore, R. S. (eds.), *Archaeology and History in Medieval and Post-Medieval Greece: Studies on Method and Meaning in Honor of Timothy E. Gregory.* London: Ashgate, pp. 53–66.

Salomon, F., Delile, H., Goiran, J.-P., Bravard, J.-P., and Keay, S., 2012. The Canale di Comunicazione Traverso in Portus: the Roman sea harbour under river influence (Tiber delta, Italy). *Géomorphologie : relief, processus, environnement*, **2012**(1), 75–90.

Sanchez, C., and Jézégou, M.-P., 2011. *Espaces littoraux et zones portuaires de Narbonne et sa région dans l'Antiquité*. Monographies d'archéologie méditerranéenne 28. Lattes: l'Association pour le développement de l'archéologie en Languedoc-Roussillon.

Sanlaville, P., Dalongeville, R., Bernier, P., and Evin, J., 1997. The Syrian coast: a model of Holocene coastal evolution. *Journal of Coastal Research*, **13**(2), 385–396.

Sarti, G., Rossi, V., Amorosi, A., De Luca, S., Lena, A., Morhange, C., Ribolini, A., Sammartino, I., Bertoni, D., and Zanchetta, G., 2013. Magdala harbour sedimentation (Sea of Galilee, Israel), from natural to anthropogenic control. *Quaternary International*, **303**, 120–131.

Schröder, B., and Bay, B., 1996. Late Holocene rapid coastal change in Western Anatolia – Büyük Menderes Plain as a case study. *Zeitschrift für Geomorphologie Supplementband*, **102**, 61–70.

Scognamiglio, E., 1997. Aggiornamenti per la topografia di Baia sommersa. *Archeologia Subacquea*, **2**, 35–45.

Shaw, I., 2000. *The Oxford History of Ancient Egypt*. Oxford: Oxford University Press.

Shaw, T., Sinclair, P., Andah, B., and Okpoko, A. (eds.), 1993. *The Archaeology of Africa: Food, Metals and Towns*. London: Routledge.

Sivan, D., Wdowinski, S., Lambeck, K., Galili, E., and Raban, A., 2001. Holocene sea-level changes along the Mediterranean coast of Israel, based on archaeological observations and numerical model. *Palaeogeography Palaeoclimatology Palaeoecology*, **167**(1), 101–117.

Sneh, A., and Weissbrod, T., 1973. Nile Delta: the defunct Pelusiac branch identified. *Science*, **180**(4081), 59–61.
Soter, S., 1998. Holocene uplift and subsidence of the Helike Delta, Gulf of Corinth, Greece. In Stewart, I., and Vita-Finzi, C. (eds.), *Coastal Tectonics*. London: Geological Society Special Publication, Vol. 146, pp. 41–56.
Soter, S., and Katsonopoulou, D., 1998. The search for ancient Helike, 1988–1995. Geological, sonar and bore hole studies. In Katsonopoulou, D., Soter, S., and Schilardi, D. (eds.), *Ancient Helike and Aigialeia*. Athens: The Helike Society Publications, pp. 67–116.
Stanley, J.-D., 2007. *Geoarchaeology: Underwater Archaeology in the Canopic Region in Egypt*. Oxford: Oxford Center for Maritime Archaeology.
Stanley, J.-D., and Bernasconi, M. P., 2006. Holocene depositional patterns and evolution in Alexandria's eastern harbor, Egypt. *Journal of Coastal Research*, **22**(2), 283–297.
Stanley, J.-D., and Jorstad, T. F., 2006. Buried canopic channel identified near Egypt's Nile Delta coast with radar (SRTM) imagery. *Geoarchaeology*, **21**(5), 503–514.
Stanley, D. J., and Warne, A. G., 1994. Worldwide initiation of Holocene marine deltas by deceleration of sea-level rise. *Science*, **265**(5169), 228–231.
Stanley, J.-D., Goddio, F., and Schnepp, G., 2001. Nile flooding sank two ancient cities. *Nature*, **412**(6844), 293–294.
Stanley, J.-D., Goddio, F., Jorstad, T. F., and Schnepp, G., 2004a. Submergence of ancient Greek cities off Egypt's Nile delta – a cautionary tale. *GSA Today*, **14**(1), 4–10.
Stanley, J.-D., Warne, A. G., and Schnepp, G., 2004b. Geoarchaeological interpretation of the Canopic, largest of the relict Nile Delta distributaries, Egypt. *Journal of Coastal Research*, **20**(3), 920–930.
Stefanakis, M. I., 2010. Western Crete: from Captain Spratt to modern archaeoseismology. In Sintubin, M., Stewart, I. S., Niemi, T. M., and Altunel, E. (eds.), *Ancient Earthquakes*. Boulder: Geological Society of America. GSA Special Paper, Vol. 471, pp. 67–79.
Stefaniuk, L., and Morhange, C., 2005. Évolution des paysages littoraux dans la dépression sud-ouest de Cumes depuis 4000 ans. La question du port antique. *Méditerranée*, **104**(1–2), 49–59.
Stefaniuk, L., Morhange, C., Saghieh-Beydoun, M., Frost, H., Boudagher-Fadel, M. K., Bourcier, M., and Noujaim-Clark, G., 2005. Localisation et étude paléoenvironnementale des ports antiques de Byblos. *Bulletin d'Archéologie et d'Architecture Libanaises*, Hors-série **2**, 19–41.
Stewart, I. S., and Morhange, C., 2009. Coastal geomorphology and sea-level change. In Woodward, J. C. (ed.), *The Physical Geography of the Mediterranean*. Oxford: Oxford University Press, pp. 385–413.
Stiros, S. C., 1998. Archaeological evidence for unusually rapid Holocene uplift rates in an active normal faulting terrain: Roman harbor of Aigeira, Gulf of Corinth, Greece. *Geoarchaeology*, **13**(7), 731–741.
Stiros, S. C., 2001. The AD 365 Crete earthquake and possible seismic clustering during the fourth to sixth centuries AD in the Eastern Mediterranean: a review of historical and archaeological data. *Journal of Structural Geology*, **23**(2–3), 545–562.
Stiros, S., 2005. Social and historical impacts of earthquake-related sea-level changes on ancient (prehistoric to Roman) coastal sites. *Zeitschrift für Geomorphologie Supplementband*, **137**, 79–89.
Stiros, S., Pirazzoli, P., Rothaus, R., Papageorgiou, S., Laborel, J., and Arnold, M., 1996. On the date of construction of Lechaion, western harbor of ancient Corinth, Greece. *Geoarchaeology*, **11**(3), 251–263.
Tallet, P., 2009. Les Égyptiens et le littoral de la mer Rouge à l'époque pharaonique. *Comptes Rendus de l'Académie des Inscriptions et des Belles-Lettres*, 2009, fasc. 2: 687–719.
Tartaron, T. F., 2013. *Maritime Networks in the Mycenaean World*. Cambridge: Cambridge University Press.
Testaguzza, O., 1970. *Portus. Illustrazione dei porti di Claudio e Traiano e della città di Porto a Fiumicino*. Roma: Julia Editrice.
Todesco, M., Rutqvist, J., Chiodini, G., Pruess, K., and Oldenburg, C. M., 2004. Modeling of recent volcanic episodes at Phlegrean Fields (Italy): geochemical variations and ground deformation. *Geothermics*, **33**(4), 531–547.
Tousson, O., 1922. *Mémoire sur les anciennes branches du Nil*. Cairo: Institut Français d'Archéologie Orientale. Mémoires presentés à l'Institut d'Egypte, Vol. 4.
Van Andel, T. H., 1989. Late Quaternary sea-level changes and archaeology. *Antiquity*, **63**(241), 733–745.
Van Beek, G., and Van Beek, O., 1981. Canaanite-Phoenician architecture: the development and distribution of two styles. *Eretz-Israel*, **15**, 70*–77*.
Van de Noort, R., and O'Sullivan, A., 2006. *Rethinking Wetland Archaeology*. London: Duckworth.
Véron, A., Goiran, J.-P., Morhange, C., Marriner, N., and Empereur, J.-Y., 2006. Pollutant lead reveals the pre-Hellenistic occupation and ancient growth of Alexandria, Egypt. *Geophysical Research Letters*, **33**(6), L06409.
Villas, C. A., 1996. Geological investigations. In Coulson, W. D. E. (ed.), *Ancient Naukratis: Volume II, The Survey at Naukratis and Environs*. Oxford: Oxbow Books. Oxbow Monograph, Vol. 60, pp. 163–175.
Vött, A., Schriever, A., Handl, M., and Brückner, H., 2007. Holocene palaeogeographies of the central Acheloos River delta (NW Greece) in the vicinity of the ancient seaport Oiniadai. *Geodinamica Acta*, **20**(4), 241–256.
Walsh, K., 2004. Caring about sediments: the role of cultural geoarchaeology in Mediterranean landscapes. *Journal of Mediterranean Archaeology*, **17**(2), 223–245.
Walsh, K., 2008. Mediterranean landscape archaeology: marginality and the culture-nature 'divide'. *Landscape Research*, **33**(5), 547–564.
Yanko-Hombach, V., Gilbert, A. S., and Dolukhanov, P., 2007a. Controversy over the great flood hypotheses in the Black Sea in light of geological, paleontological, and archaeological evidence. *Quaternary International*, **167–168**, 91–113.
Yanko-Hombach, V., Gilbert, A. S., Panin, N., and Dolukhanov, P. M. (eds.), 2007b. *The Black Sea Flood Question: Changes in Coastline, Climate and Human Settlement*. Dordrecht: Springer.
Zong, Y., Chen, Z., Innes, J. B., Chen, C., Wang, Z., and Wang, H., 2007. Fire and flood management of coastal swamp enabled first rice paddy cultivation in east China. *Nature*, **449**(7161), 459–462.

HARRIS MATRICES AND THE STRATIGRAPHIC RECORD

Edward Cecil Harris
National Museum of Bermuda, Sandys, Bermuda

Synonyms

Archaeological stratigraphy; Harris matrix; Stratigraphic excavation; Stratigraphic sequences

Definitions

Archaeological stratigraphy is the discipline that encompasses the study of all aspects of stratification on archaeological sites, including both human and geological formations. It is concerned with (1) the landscape components of stratification, i.e., surfaces embedded within the site, and with the contents of deposits, including artifacts and other contained remains, and (2) the sequential and chronological relationships between stratigraphic units. Stratigraphic studies lay the foundation for all later analyses of the surfaces and portable remains of archaeological sites; they are fundamental to any archaeological research involving excavation, which necessarily destroys stratigraphic evidence (but translates it into a stratigraphic archive) and removes samples of the remains found in deposits for analysis and preservation.

Stratigraphic excavation is the examination of archaeological sites (including geological components) using the principles of archaeological stratigraphy, wherein the latest units of stratification are removed before earlier ones, following the recording of "surfaces without deposits" and the "surfaces of deposits." It is axiomatic that the excavator follows and records the contours of surfaces as they are found and before excavation of underlying deposits, for that is the only way in which the landscape of the site can be reconstructed. It is also axiomatic that the reconstruction of archaeological sites is the reconstruction of the surfaces buried within the site, not the deposits lying above and below these surfaces, and that such a reconstruction is one of the principal goals of archaeological work on physical sites.

Stratigraphic sequences for archaeological sites are formed by the interpretation of the surfaces and deposits found during excavation and the placement of such universal stratigraphic units into a sequence in relative time. Such sequences represent the four dimensions of stratification, that is, the two dimensions of surfaces (area, length and width), the single dimension of deposits (depth or height), and, fourth, the relative time dimensions connecting the units of stratification on a site. Stratigraphic sequences form the testing pattern for much of the later analyses of the landscape and portable remains of a site. They are unique to each site, and that is their value to any form of archaeology that includes excavation, as well as for historical and anthropological studies. As stratigraphic sequences are all about time, and they form a unique "calendar," or "DNA" identifier for a site, they do not exist unless translated from the immaterial (surfaces) and material (deposits) evidence of stratification into a diagram. Since 1973, the Harris Matrix has provided the means for expressing such sequences in a diagrammatic form. Previously, "sections," or profiles, seen on a plane through a site, at one position or line only, were thought to fulfill that role. They cannot truly do so, as they represent only one dimension, that of depth, or height, on only one plane through a site.

Harris Matrices represent the stratigraphic sequences of archaeological sites in diagrams in which the oldest stratigraphic units are at the bottom, and later, or younger, stratigraphic units are at the top. Constructed on principles first delineated in the 1970s (Harris, 1975; Harris, 1977; Harris, 1979b), the Matrix, if assembled on an archaeological site during the excavation of stratigraphic units (archaeological and geological), will reflect in part the stratigraphic excavation of the site, with the sequence being built from the top, or latest stratigraphic units coming into place first, followed beneath by earlier units as excavation progresses. If assembled during the course of stratigraphic excavation, the Harris Matrix, or stratigraphic sequence, will be completed for a site, or part of a site, when excavation ceases. As the diagram is compiled without regard for the contained remains, but only in relation to the interpretation of the stratigraphic units, the Harris Matrix method is of universal application, since stratigraphic units are everywhere the same: a series of surfaces and deposits. With those methods in mind, any archaeologist, accountant-like, can audit the records of archaeological sites anywhere in the world and quickly ascertain if the "books" (the records) reflect that a site is being excavated and recorded by the principles of archaeological stratigraphy and that a valid and true stratigraphic sequence has been, or is being, compiled.

Introduction

In the historical development of the science of archaeology, where excavation of sites was a factor, it is fair to say that the process occurred in four phases. First, archaeologists dug up sites to find artifacts, for it was the portable remains, particularly those of intrinsic value, that were of paramount interest. Second, as the twentieth century progressed, architectural remains took on a value similar to that of portable artifacts, and many excavations consisted primarily of trenching to follow walls. Thus, the second historical phase came into being. Nonetheless, much early excavation was not conducted on stratigraphic principles, although one cannot often prove such an assertion; since the evidence was not often stratigraphically recorded, one cannot therefore match the recorded evidence of stratification with suppositions on excavation methods.

The third phase, wherein archaeologists became concerned with stratification and stratigraphic principles in detail, began after the profession had been in existence for over a century. This third phase began in earnest in the 1950s with the publication of Dame Kathleen Kenyon's *Beginning in Archaeology* (Kenyon, 1952) and Sir Mortimer Wheeler's *Archaeology from the Earth* (Wheeler, 1954), books that detailed new methods of stratigraphic excavation. The fourth phase began in the early 1970s, with the invention of the "Harris Matrix" in 1973, which was first published 2 years later in *World Archaeology* as "The stratigraphic sequence: a question of time" (Harris, 1975). A full description of the new methods in stratigraphic archaeology appeared in *Principles of Archaeological Stratigraphy* (Harris, 1979a; Harris, 1989). The title of the latter work suggested that an "archaeological stratigraphy" was inherent in the nature of stratification on archaeological sites and that principles of geology were not entirely apt for places formed primarily by human agency.

For a while, some scholars did not agree with that view. They thought that principles of geological stratigraphy were fundamental to archaeology (Gasche and Tunca, 1983; Farrand, 1984; Collcutt, 1987). Geology, however, had not provided archaeology with a method for compiling stratigraphic sequences. In the nineteenth century, archaeology took its stratigraphic principles primarily from the Law of Superposition, which generally asserts that if one deposit lies beneath another, the lower unit is older. An exception includes the case of consolidated, hard rock formations that have been overturned due to folding under pressure, thereby reversing the strata in places. In an archaeological context, where one must assume a "loose rock" analogy, any "overturning" results in the formation of new surfaces and deposits. Only the artifacts are "reversed" in sequence or displaced chronologically. The stratigraphic units in which they are found are newly formed due to the unconsolidated nature of most deposits on archaeological sites.

One of the components taken from geology that established the paradigm for archaeology until the 1970s was the section, or profile, cut vertically through a site. It was often recorded and presented as a "stratigraphic sequence," although that phrase was seldom used. The section as the supreme stratigraphic paradigm became enshrined in archaeological thought with the advent of the "Wheelerian Grid," in which a site would be excavated in square trenches with intervening "balks" that preserved the profiles. This approach inhibited a full understanding of the stratigraphic history of a site and the creation of true stratigraphic sequences, however. Within the boxlike excavation units, the details pertaining to embedded surfaces were largely destroyed by the excavation of the deposits, mostly without recording; and most excavators at the time did not understand that it is the surfaces, not the deposits, that hold the keys to complete comprehension of site stratification. Without a record of the surfaces, the stratigraphic sequence of a site cannot be compiled, as many archaeologists can attest after attempting to do so subsequent to the close of excavation. Surfaces, like time, do not exist unless recorded in a diagram. A strict focus on the digging process explains to some degree how earlier archaeologists thought of themselves as excavating the material (deposits) while they ignored the immaterial (surfaces.) They did not realize that, in stratigraphic interpretation, surfaces cover the entire site and are represented throughout the volume of its deposits, whereas a section and its associated stratigraphic sequence is true only along the plane through the site on which it appears as a vertical image, representing only the depth or height dimension of a site at that point.

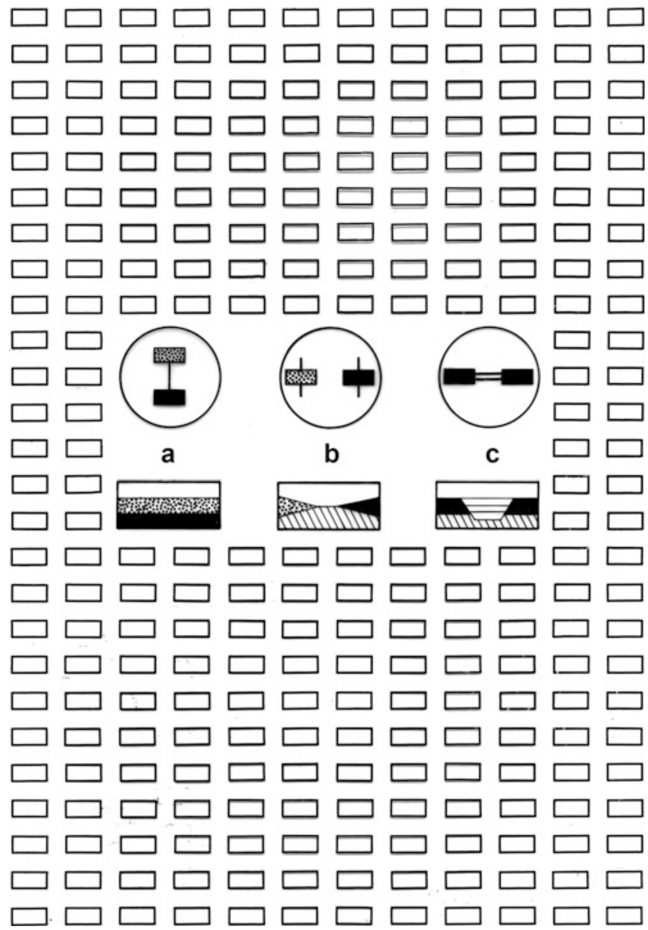
Some archaeologists in the late 1960s were aware that the section and Wheelerian Grid were detrimental to the understanding of sites, and that they were more an expression of a change in excavation methodology. Their new method, known as "open-area excavation," allowed for temporary balks and the ability to see the whole of a site without the interruptions of permanent balks (a surface, rather than section, approach). It did not translate into a full awareness of the central value of every surface in stratigraphic analysis, however, and most individual surfaces were not recorded. What transpired was the creation of "composite plans" that were thought to reflect major periods on a site, but in reality they often recorded only the "period of excavation." Given the overlap of surfaces and deposits, only parts of some surfaces were recorded, thus leaving a "data hole" where the unseen parts of those surfaces were lost because they were not recorded (Biddle and Kjølbye-Biddle, 1969; Barker, 1977). It is now known that if every surface is recorded, a phase or period plan can be reconstructed for the site at every turn, including when it was altered by the addition or destruction of stratigraphic units. Thus, a site with a thousand surfaces can have, if desired, a thousand phases or period plans, but such plans will depend upon the later analyses of contained remains, which will "move" surfaces up or down a string in relative time in a Harris Matrix, when coupled with a chronometric time scale on the side of the diagram. Hence, well into the mid-1970s, excavators were locked into the main tool of their trade – digging – and while stratigraphic excavation was continually refined, recording methods were stuck in the geological paradigm of the section.

After the invention of the Harris Matrix, it took several years to discern what archaeologists were not doing correctly, in terms of stratigraphic recording, so that true stratigraphic sequences could be compiled. The key, which was suggested by English archaeologist Laurence Keen, was the recording of each and every surface, in what were known as "single-layer," or later more correctly as "single-context" plans (since layers, or deposits, are not surfaces). For example, many surfaces are stand-alone stratigraphic units without an associated deposit, such as the surface of a trench cut into preexisting strata for the insertion of some installation like a water main. With Brian Hobley's assistance in 1974, single-context planning and the Harris Matrix system was used for the first time on a large excavation by the Museum of London with resounding success. Exploring a prehistoric ditch in Winchester, England, in 1975, Patrick Ottaway conducted the first experiment on an archaeological site to record each surface before it was excavated away (Harris and Ottaway, 1976). The experiment meant that the landscape of the site (the stratigraphic reality that people lived on or with, as people did not live in deposits) could be reconstructed simply by overlaying the plan of each surface unit, in stratigraphic order, beginning at the bottom of the ditch and working upwards to the modern surface that existed pre-excavation.

As an aside and a summary to this brief historical overview of archaeological stratigraphy, the "digger mindset" persisted for the first years of the Harris Matrix, as the diagrams were initially called "layer charts," layer being the then common name for deposits that can be dug up. It was only after a time that the understanding emerged that a Harris Matrix diagram was in fact the representation of the stratigraphic sequence of a site and, as such, could be compiled only if full attention were paid to the surfaces, their recording, and interpretation. The Harris Matrix has proved to be a valid method and has created a new stratigraphic paradigm for archaeology, prompting the statement that "For the first time, stratigraphy became truly *independent* of the section. . .it was quite a momentous occasion in the history of field archaeology in Britain" (Lucas, 2001, 57). The simple principles and methods of the Harris Matrix are explained below.

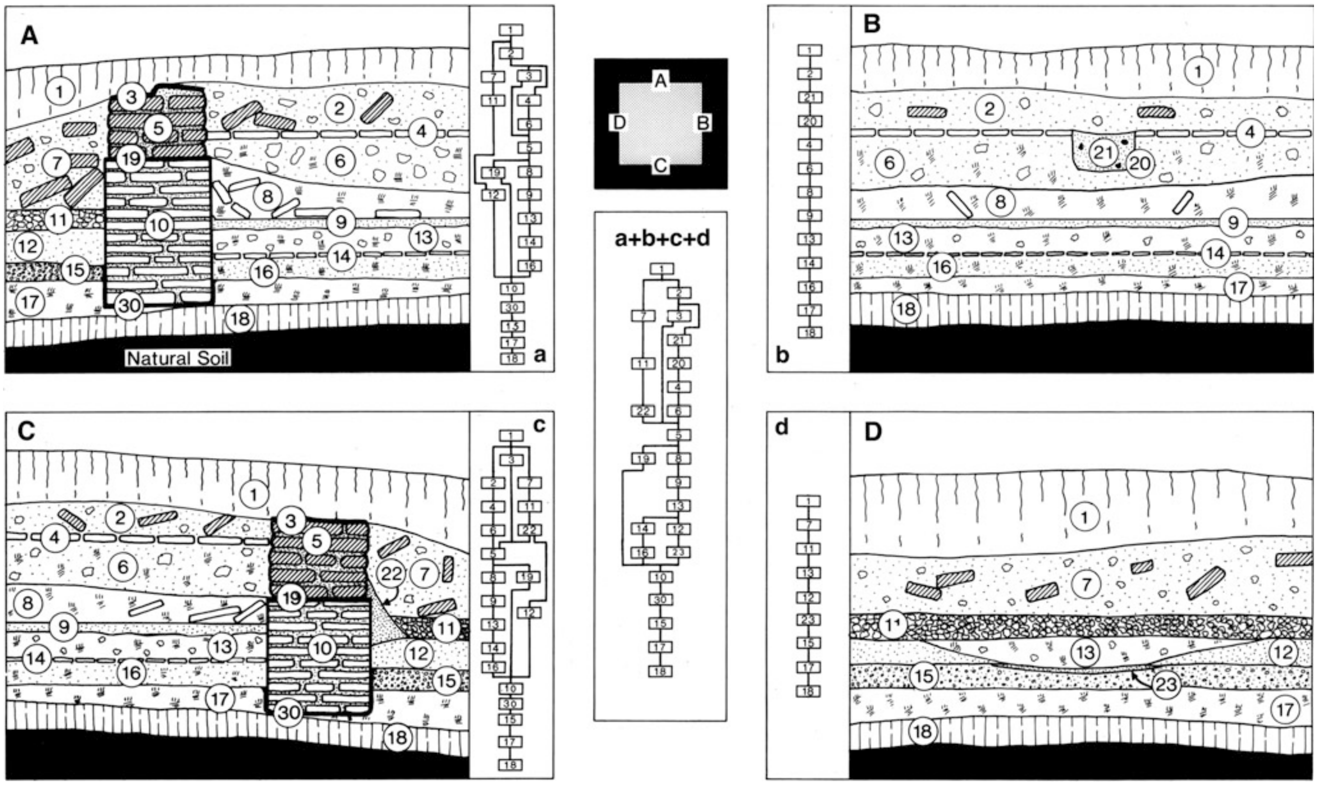
Principles of archaeological stratigraphy

Archaeological Stratigraphy is governed by a set of laws, elucidated by Harris (1979a, b). The reason for establishing such laws is that archaeological sites, which are made by people, do not generally conform to the laws of nature, as expressed in the tenets of geological stratigraphy. The laws borrowed by earlier archaeologists from geological sources ultimately proved inadequate to deal with the complexities of archaeological stratification, especially in intensely built-up sites. The Earth is now girdled with human stratification, some of it perhaps larger than any geological deposit; consider, for example, the Interstate Highway System of the United States, which stretches as a stratigraphic surface from coast to coast, and if joined with other highways, from Alaska to Patagonia. The Law of Superposition states generally that if a unit is below another, it is older. This relationship prevails unless surfaces without deposits are encountered. In such a case, applying the Law of Stratigraphical Succession resolves the issue. This law states that a unit takes its place in the stratigraphic sequence above the latest unit that the surface unit "cut" through. Thus, in a traditional section, a disused "tube" of the London Underground (a surface with no deposited fill) may appear below Roman deposits and give the impression of being earlier, but if traced in plan, the tube's surface reveals that it was cut down through overlying stratification. Therefore, the surface – and all of its contained units – emerges from its apparently contradictory physical situation and assumes its true position in relative time within the stratigraphic sequence: above (=historically after) units of the later Victorian period. The Law of Original Horizontality gives perspective on the nature of the layering of deposits, while the Law of Original Continuity is important, as it helps explain why stratigraphic units are interrupted, such as when a utility trench is dug through earlier surfaces and deposits. Those laws and methods of recording in archaeological stratigraphy provided the building blocks for the compilation of a Harris Matrix or stratigraphic sequence.



Harris Matrices and the Stratigraphic Record, Figure 1 A blank Harris Matrix sheet with inserts showing (*A*) two units that are in a superpositional relationship, (*B*) two units that are not in a superpositional relationship, and (*C*) two units that may be correlated (optional).

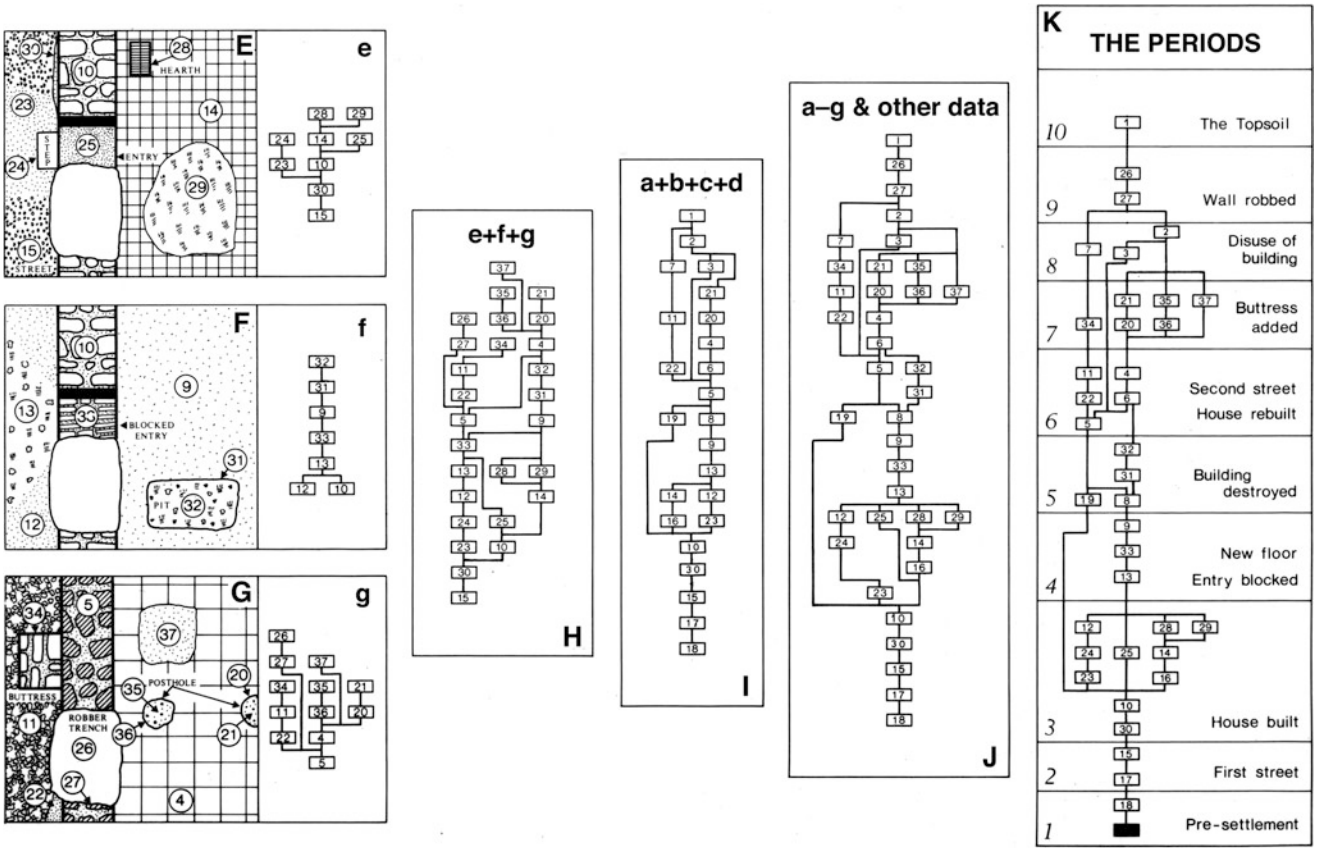
The compilation of a Harris Matrix, or stratigraphic sequence, is based on the question of relative time. To ask, "Which came first?" of any two stratigraphic units in superposition, one must determine which one, or which part of one, lies on top of the other unit, or part of it. The units are placed in the sequence with the lower one below and the later one above. A line emerging from the top of the box representing the lower unit and connecting to the bottom of the box representing the upper unit defines that stratigraphic relationship, and this relationship is fixed immutably at the time of observation and recording (Figure 1A). These relative time relationships cannot be broken, even if the progression of artifacts embedded within the vertical string of units suggests otherwise in terms of chronometric time. The presence of artifacts apparently out of sequence must be explained by other agencies (Harris and Reece, 1979), for the stratigraphic sequences reflect the order of deposition and creation of the stratigraphic units and must be compiled without



Harris Matrices and the Stratigraphic Record, Figure 2 A Harris Matrix is prepared for each section of an excavation unit, and then, as they are all actually one section, a single stratigraphic sequence is compiled by combining a+b+c+d and removing redundant lines (see Harris, 1989).

reference to any contained remains. To alter the stratigraphic sequence on the basis of contained remains is to alter the position of the associated surfaces, which cannot be moved into new positions in the sequence without potentially confounding and contradicting the physical buildup of the site over time. Contained remains are in effect locked into place by the position of the deposit that encloses them in the stratigraphic sequence. Therein lies part of the formidable and irreplaceable value of the Harris Matrix to all future analysis of the stratigraphic importance of a site's landscape history as well as the analysis of all contained remains and their significance in the site's cultural history. The other two relationships that are recognized are that two units of stratification need not be in superposition (Figure 1B) and that two parts of a once whole unit may be correlated with an = sign between two unit boxes (Figure 1C). The last is optional, while the first two are mandatory. The boxes of course carry their own unique identifier number for the individual stratigraphic units they represent; a deposit or unit that has been subdivided by later alterations to the site must be given separate numbers for each part, as each part is now a separate unit in the stratification.

Using the first two relationships only, the Harris Matrix can be built up, unit by unit, as excavation and recording proceed on the site; the third correlation relationship is optional. As each stand-alone surface or surface of a deposit is identified, numbered, and recorded in plan and in recording sheets, the unit can be added to the sequence. As excavation is generally done by hand, and only so many units can be excavated in one day, it should be easy to keep the diagram of the stratigraphic sequence updated each day. If one were dealing with a trench excavated by machine, so that the only stratigraphic evidence to record was that of profiles after the machine had exposed them, then each section would have its own sequence. If, however, the sections of a hole or trench were connected, the different section sequences would need to be joined together to form the single sequence representing the summary sequence of all the sections, as is demonstrated in Figure 2. That sequence would be further altered and elongated if surface data from within an excavation were available to be factored into the diagram to make the fullest possible stratigraphic sequence for the site (Figure 3). If one excavates the entire site stratigraphically, however, making surface plans and notations on superpositional relationships as work proceeds, the sequence is built up (down, during excavation), almost automatically, without the necessity of joining, say, several section sequences into a single one. That is to say that



Harris Matrices and the Stratigraphic Record, Figure 3 Harris Matrices are prepared for three plans, E, F, and G, and the sequences are combined as e+f+g with that of the sections in Figure 2 (a+b+c+d), and those two sequences are combined with other stratigraphic data not appearing in the plans or in the sections, to form the full stratigraphic sequence for the site in K, which can then be divided into periods based on contained artifacts.

some of the issues above apply only to sites which were not excavated while using the Harris Matrix to compile the stratigraphic sequence as work proceeds; this applies to many excavations worldwide that were conducted before, and since, the advent of the Matrix and its associated and necessary concepts on the principles of archaeological stratigraphy.

In the assigning of identifier numbers, it is axiomatic that all surfaces that do not have deposits, such as trenches and holes of whatever variety (postholes, ditches, wells, etc.), must be given a number following the Law of Stratigraphical Succession in determining the position of such "interfaces" in the stratigraphic sequence. If they are not numbered, the stratigraphic sequence then cannot be an accurate listing of the site formation progression. Surfaces that define the upper boundaries of deposits need not be numbered, although if they were, it would make more sense for the sequence and its periodization, since the surfaces and not the deposits mark the major "living" phases or periods on a site, and they often represent vastly greater time periods than the deposits which "support" such surfaces. That is, in the duality of stratification, its waxing and waning, its erosion and deposition, there are (a) periods of deposition (placing material into nonuse) and (b) periods of use, or nondeposition. For example, most surfaces of the Coliseum in Rome have been in use for a couple of thousand years, whereas the "supporting" stonework was "deposited," or put in place, only once. Presently, in most Harris Matrix diagrams, the surfaces of deposits are indirectly represented by the lines connecting the unit boxes, as they are not generally given unique identifiers. Perhaps they should be numbered as identifiers because they would then be tied into the plans of surfaces. Supporting deposits would appropriately have their own number, to which all contained remains would be tied.

Post-excavation analyses and reconstruction of sites

The Harris Matrix stands at the center between two pyramids of archaeological knowledge, the upper, or later, one resting atop the earlier one in an inverted position with the two points in contact. From the lower pyramid, all of the stratigraphic data from the site flow upward into the creation of the stratigraphic sequence at its apex. The upper, inverted pyramid represents all the later analyses, interpretations, artifact curation, and records archiving, most of which must take as its foundation the stratigraphic sequence, or be tested against it. The stratigraphic sequence is central to those two pyramids of data and knowledge, the lower one representing all the acquisition of new information from the physical site (stratification) and the sample collecting of the remains contained within the deposits – i.e., artifacts and ecofacts. The sum of all raw data steadily adds to our knowledge about the past when it is analyzed in the upper pyramid, which funnels upward and outward, for such analyses may go on for generations to come. Once analyses have taken place for various types of portable remains, the results of those studies are reconsidered in the light of the stratigraphic sequence, which can change shape (but not its fixed relationships) by elongation, in relation to a sidebar scale in calendar, or chronometric time. Such studies help to determine the position of "floating units" relative to other units with which they have no superpositional relationship in the sequence. Depending on the results of analysis, they can slide up or down on their separate strings relative to one another in the Harris Matrix diagram. This process invokes the permutations of stratigraphic sequences as originally raised in Dalland (1984), Harris (1984), and elaborated by Bibby (2002) and Roskams (2001); it is a major issue for archaeological interpretation. Subsequently, the final phase and period diagrams can be arranged for the site, based partly on the chronological input from the contained remains. Those images are represented in plan or map form for the periods of nondeposition (combined surfaces), and for the periods and phases of deposition, they are represented in section drawings, the latter showing the shape and volume of the stratification along a plane through the site. If individual surface plans are recorded with elevations, then on computers with GIS capabilities, sections can be constructed along any line through the site, an option that is impossible during excavation, as we must excavate stratigraphically from the top (surface), not from the side (section) of the stratified sequence. One of the main goals of excavation is to be able to reconstruct the site, which is to say, reconstruct its surfaces, its periods of usage. The recording of individual surfaces of each stratification unit is the only way to accomplish that reconstruction, for no matter the number of sections that may be recorded, there will never be enough to reconstruct the surfaces and therefore to allow for the full reconstruction of the site. That provable assertion should bring to an end the method known as "arbitrary excavation," whereby, in what appears to be a very precise and scientific method, a site is excavated entirely in predetermined levels. Such an excavation strategy results in the formation of false surfaces and the destruction of the original stratified surfaces before they are recorded. The original surfaces do not follow precise horizontal levels at uniform elevations on most sites. No site excavated in arbitrary levels can be reconstructed because its surface evidence is in reality a "sequence of excavation" levels, not a stratigraphic sequence compiled by following the contours of the original stratigraphic units.

Summary

While fundamental to the science of archaeology, the subject of archaeological stratigraphy received little elaboration of its basic principles for many decades. These principles had been borrowed from geology in the nineteenth century. A paradigm shift occurred in the 1950s when Kenyon and Wheeler brought attention to stratigraphic excavation, recording sections to include distinct lines for surfaces between deposits. They began to examine the methods of phasing (that is, the compilation of stratigraphic sequences in the first instance). In that phase, the section was seen as the stratigraphic sequence and surfaces not in the section were largely ignored. A subsequent paradigm shift added surfaces to the equation. Surfaces are, in effect, two major dimensions of stratification within archaeological sites, but the advent of "open-area excavation" by Philip Barker and others represented a shift largely in method of excavation and not a fundamental change in recording methods. In 1973, a fundamental paradigm shift occurred, which added a fourth dimension: time. This development brought not only the production of stratigraphic sequences in Harris Matrices, but also the acknowledgment and recording of surfaces lacking deposits, which are immaterial and can be seen only if recorded as a plan drawing The abiding importance of surfaces is that they represent the periods of time when the site was in use, i.e., when it was being lived on, and as such they usually reflect the passage of far more time than the deposits that were laid down, or constructed, to form those surfaces (Harris et al., 1993). As the eminent geologist, Charles Lyell, once wrote, stratification "is *undesignedly* commemorative of former events" (Lyell, 1875, I, 3), and thus, to add a modern corollary in archaeology, "stratigraphic sequences, being composed from the evidence of *undesigned* stratification, are unbiased testing patterns for archaeological sites." The Harris Matrix and associated methods are the only way to *see* such relative time sequences on archaeological sites, no matter the origins of the deposits or the cultural and ecological material remains contained within the deposits. Harris Matrices are of universal application and are thus becoming the "industry standard" in many countries around the world.

Bibliography

Barker, P., 1977. *Techniques of Archaeological Excavation*. London: Batsford.

Bibby, D. I., 2002. Permutations of the multilinear stratigraphic sequence: nature, mathematics and consequences. Paper presented at Workshop 7 "Archäologie und Computer" (20–22 November 2002). Powerpoint file on CD. Vienna: Phoibos Verlag.

Biddle, M., and Kjølbye-Biddle, B., 1969. Metres, areas, and robbing. *World Archaeology*, **1**(2), 208–219.
Collcutt, S. N., 1987. Archaeostratigraphy: a geoarchaeologist's viewpoint. *Stratigraphica Archaeologica*, **2**, 11–18.
Dalland, M., 1984. A procedure for use in stratigraphical analysis. *Scottish Archaeological Review*, **3**(2), 116–127.
Farrand, W. R., 1984. Stratigraphic classification: living within the law. *Quarterly Review of Archaeology*, **5**(1), 1–4.
Gasche, H., and Tunca, Ö., 1983. Guide to archaeostratigraphic classification and terminology: definitions and principles. *Journal of Field Archaeology*, **10**(3), 325–335.
Harris, E. C., 1975. The stratigraphic sequence: a question of time. *World Archaeology*, **7**(1), 109–121.
Harris, E. C., 1977. Units of archaeological stratification. *Norwegian Archaeological Review*, **10**(1–2), 84–94.
Harris, E. C., 1979a. *Principles of Archaeological Stratigraphy*. London: Academic Press.
Harris, E. C., 1979b. The laws of archaeological stratigraphy. *World Archaeology*, **11**(1), 111–117.
Harris, E. C., 1984. The analysis of multilinear stratigraphic sequences. *Scottish Archaeological Review*, **3**(2), 127–133.
Harris, E. C., 1989. *Principles of Archaeological Stratigraphy*, 2nd edn. London: Academic Press.
Harris, E. C., and Ottaway, P. J., 1976. A recording experiment on a rescue site. *Rescue Archaeology*, **10**, 6–7.
Harris, E. C., and Reece, R., 1979. An aid for the study of artefacts from stratified sites. *Archaeologie en Bretagne*, **20–21**, 27–34.
Harris, E. C., Brown, M. R., III, and Brown, G. J., 1993. *Practices of Archaeological Stratigraphy*. London: Academic Press.
Kenyon, K. M., 1952. *Beginning in Archaeology*. London: Phoenix House.
Lucas, G., 2001. *Critical Approaches to Fieldwork: Contemporary and Historical Archaeological Practice*. London: Routledge.
Lyell, C., 1875. *Principles of Geology*, 12th edn. London: Murray.
Roskams, S., 2001. *Excavation*. Cambridge: Cambridge University Press.
Wheeler, R. E. M., 1954. *Archaeology from the Earth*. Oxford: Clarendon Press.
www.harrismatrix.com: Downloads of the book on the Harris Matrix, *Principles of Archaeological Stratigraphy*, may be obtainable for free at this web site in English, German, Hungarian, Polish, Slovene and Spanish editions.

Cross-references

Archaeological Stratigraphy
Chronostratigraphy
Field Survey
Landscape Archaeology

HAUA FTEAH

Chris O. Hunt
School of Natural Sciences and Psychology, Liverpool John Moores University, Liverpool, UK

Synonyms

The Haua

Introduction

The Haua Fteah, in northeastern Libya (32°53′59″ N; 22°03′05″ E), is a large and imposing cave 1 km south of the Mediterranean coast at an elevation of 67 m asl. It was excavated in the 1950s by Charles McBurney (McBurney, 1967) and re-excavated between 2007 and 2012 by Graeme Barker and Tim Reynolds (Barker et al., 2007, 2008, 2009, 2010, 2012; Rabbett et al., 2013).

Geomorphology

The cave lies on the edge of a large doline, or sinkhole, one of several in the area. It most probably reached its present morphology when the doline intersected with a pre-existing cave of phreatic origin, with further modification by granular disintegration and episodic roof falls.

The cave fill

The filling of the cave is contiguous with, and interfingers with, the doline fill. The sequence contains 15.5 m of well-stratified sediments dating from late OIS 6 to the present. Most of the sequence consists of silty diamicts (poorly sorted deposits with different particle sizes) and silts deposited by mudflow and wash originating outside the cave and most probably reflecting rare extreme rainfall events and perhaps climatically disrupted vegetation. Pedogenic features and carbonate induration are episodically developed, reflecting phases with low rates of sedimentation and well-developed vegetation cover outside the cave (Inglis, 2012). Breccias ultimately derived from roof collapse and emplaced by debris avalanche are occasionally present, but they comprise the dominant lithofacies in late MIS 3 and MIS 2. Silts, silty diamicts, and breccias characterize the early mid-Holocene, with a facies shift to diamicts and stable-burning deposits caused by land use changes following the Greek invasion in 621 BC and a change in the use of the cave from residential to livestock penning. Gravels derived from alluvial fan deposits outside the cave were spread on top of the fill during military activity in the 1980s. Throughout the cave's history, sedimentation in the Haua Fteah was characterized by long periods of stillstand separated by extremely rapid and often catastrophic sedimentation events incorporating, on occasion, materials from older levels (Hunt et al., 2010, 2015). For example, the Holocene sequence appears to have accumulated as the result of only 24 significant sedimentation events.

Archaeology

The cave's archaeological record preserves a rich sequence featuring 'pre-Aurignacian' (elongate) Middle Stone Age (MSA), Levallo-Mousterian MSA, Dabban (Upper Paleolithic), Epipaleolithic, Neolithic, and Graeco-Roman artifacts plus a wide range of biological indicators including shell, bone, plant remains, pollen, and phytoliths. Human mandibles of early modern type were found near the base of the Levallo-Mousterian

MSA, provisionally dated to ca. 70,000 years ago (Douka et al., 2014). A Graeco-Roman temple was found near the top of the sequence.

Bibliography

Barker, G., Hunt, C., and Reynolds, T., 2007. The Haua Fteah, Cyrenaica (Northeast Libya): renewed investigations of the cave and its landscape 2007. *Libyan Studies*, **38**, 93–114.

Barker, G., Basell, L., Brooks, I., Burn, L., Cartwright, C., Cole, F., Davison, J., Farr, L., Grün, R., Hamilton, R., Hunt, C., Inglis, R., Jacobs, Z., Leitch, V., Morales, J., Morley, I., Morley, M., Pawley, S., Pryor, A., Reynolds, T., el-Rishi, H., Roberts, R., Simpson, D., Twati, M., and van der Veen, M., 2008. The Cyrenaican Prehistory Project 2008: the second season of investigations of the Haua Fteah cave and its landscape, and further results from the initial (2007) fieldwork. *Libyan Studies*, **39**, 175–221.

Barker, G., Antoniadou, A., Barton, H., Brooks, I., Candy, I., Drake, N., Farr, L., Hunt, C., Abdulhamid Ibrahim, A., Inglis, R., Jones, S., Morales, J., Morley, I., Mutri, G., Rabett, R., Reynolds, T., Simpson, D., Twati, M., and White, K., 2009. The Cyrenaican Prehistory Project 2009: the third season of investigations of the Haua Fteah cave and its landscape, and further results from the 2007–2008 fieldwork. *Libyan Studies*, **40**, 55–94.

Barker, G., Antoniadou, A., Armitage, S., Brooks, I., Candy, I., Connell, K., Douka, K., Drake, N., Farr, L., Hill, E., Hunt, C., Inglis, R., Jones, S., Lane, C., Lucarini, G., Meneely, J., Morales, J., Mutri, G., Prendergast, A., Rabett, R., Reade, H., Reynolds, T., Russell, N., Simpson, D., Smith, B., Stimpson, C., Twati, M., and White, K., 2010. The Cyrenaican Prehistory Project 2010: the fourth season of investigations of the Haua Fteah cave and its landscape, and further results from the 2007–2009 fieldwork. *Libyan Studies*, **41**, 63–88.

Barker, G., Bennett, P., Farr, L., Hill, E., Hunt, C., Lucarini, G., Morales, J., Mutri, G., Prendergast, A., Pryor, A., Rabett, R., Reynolds, T., Spry-Marques, P., and Twati, M., 2012. The Cyrenaican Prehistory Project 2012: the fifth season of investigations of the Haua Fteah cave. *Libyan Studies*, **43**, 115–136.

Douka, K., Jacobs, Z., Lane, C., Grün, R., Farr, L., Hunt, C., Inglis, R. H., Reynolds, T., Albert, P., Aubert, M., Cullen, V., Hill, E., Kinsley, L., Roberts, R. G., Tomlinson, E. L., Wulf, S., and Barker, G., 2014. The chronostratigraphy of the Haua Fteah cave (Cyrenaica, northeast Libya). *Journal of Human Evolution*, **66**(1), 39–63.

Hunt, C., Davison, J., Inglis, R., Farr, L., Barker, G., Reynolds, T., Simpson, D., el-Rishi, H., and Barker, G., 2010. Site formation processes in caves: the Holocene sediments of the Haua Fteah, Cyrenaica, Libya. *Journal of Archaeological Science*, **37**(7), 1600–1611.

Hunt, C. O., Gilbertson, D. D., Hill, E. A., and Simpson, D., 2015. Sedimentation and chronologies in archaeologically-important caves: problems and prospects. *Journal of Archaeological Science*, **56**, 109–116.

Inglis, R. H., 2012. Human occupation and changing environments during the middle to later stone age: soil micromorphology at the Haua Fteah, Libya (unpublished PhD thesis). University of Cambridge.

McBurney, C. B. M., 1967. *The Haua Fteah (Cyrenaica) and the Stone Age of the South-East Mediterranean*. Cambridge: Cambridge University Press.

Rabbett, R., Farr, L., Hill, E., Hunt, C., Lane, R., Moseley, H., Stimpson, C., and Barker, G., 2013. The Cyrenaican Prehistory Project 2012: the sixth season of excavations in the Haua Fteah cave. *Libyan Studies*, **44**, 113–125.

HEARTHS AND COMBUSTION FEATURES

Susan M. Mentzer
Institute for Archaeological Sciences, University of Tübingen, Germany
School of Anthropology, University of Arizona, Tucson, AZ, USA

Definitions

Hearth. A structured and spatially discrete fire, typically of wood, built on the ground surface or a prepared substrate and intentionally lit by people.

Combustion feature. A concentrated deposit of burned materials in an archaeological site.

Introduction

Humans have interesting and complicated relationships with fire. The production and control of fire is a behavior that many believe increased the evolutionary fitness of our hominin ancestors and allowed our species to colonize and survive in the extreme northern and southern latitudes of our planet. Ethnographic and historical studies reveal many ways in which humans utilize fire as a technology for landscape modification; personal heating and heating of spaces; production of materials such as ashes or charcoal; transformation of materials from one state to another in the form of cooking, firing, smelting, or cremation; and the production of light and smoke. Humans also use fire in less tangible ways as a form of communication between each other and to other organisms. For example, fire offers protection not only against the cold but against carnivores and other people. Likewise fire can be used as a tool of physical destruction, ranging in scale from the disposal of domestic trash to the leveling of villages, as well as a tool of psychological destruction. Fires provide atmosphere and serve as foci for social activities that range from casual conversations to ritual and religious practice.

For archaeologists, identification of traces of burning in primary and secondary contexts can be informative about pyrotechnology as well as organization of space within a site. The places where humans produced or used fire are significant to archaeologists because these localities may have served many functions, both primary and secondary, such as cooking, social, and ritual spaces. Furthermore, identification of areas where burnt materials were deposited can be informative about peripheral zones within the site, intentional acts of curation, or postdepositional processes that served to redistribute anthropogenic materials.

The study of ancient fire use has in the past been accomplished by so-called archaeological generalists. Exceptions to this rule include the study of ancient pyrotechnologies such as ceramic production and metallurgy, which have been conducted by archaeological chemists. Lack of specialization in the study of fire use may be due to assumptions about the ease with which hearths and other types of combustion features can be identified and interpreted in the field. More recently, and driven in part by the true complexity of such identifications and interpretations as well as the need to evaluate critically the evidence for early controlled use of fire (e.g., Roebroeks and Villa, 2011), geoarchaeologists have begun to take a leading role in the identification of ancient fire.

Geoarchaeology provides an ideal approach to the study of combustion features principally because a majority of the analytical techniques used to identify burned materials are derived from the geosciences. These techniques include optical petrology, stable isotope geochemistry, and mineralogy (see below). In addition, combustion produces fine-grained materials that are typically classified by archaeologists as "sediment," and features composed of burned materials cannot be removed from the site and studied in the same way that one might study a stone tool or ceramic vessel. Geoarchaeologists have therefore developed analytical tools that facilitate integrative analyses of combustion features, including the collection of subsamples that can be studied in a laboratory setting. Furthermore, combustion features are impacted by taphonomic processes, and their study can easily fit within broader geoarchaeological research goals that include reconstruction of site formation processes. Following identification, the study of combustion features is ultimately best accomplished through collaboration between the geoarchaeologist(s) and specialists in architecture, ancient materials, and other areas. Nevertheless, it is entirely appropriate for a geoarchaeologist to be involved and actively engaged in the interpretation of combustion features in terms of individual human behavior and human social systems.

Types of combustion features

As deposits of burned materials in archaeological sites, combustion features are neutral with regard to human agency, that is, they can be produced by natural or anthropogenic causes. Combustion features consist of burned materials, including ashes, charcoal and other forms of charred plant material, heated stone, burned bones, glasses, and slags, with or without substrates and associated architectural elements that were directly exposed to heat. It is important to note that morphology and physical forms, including the spatial relationship between the heated materials and substrate, can vary according to, or independent of, function.

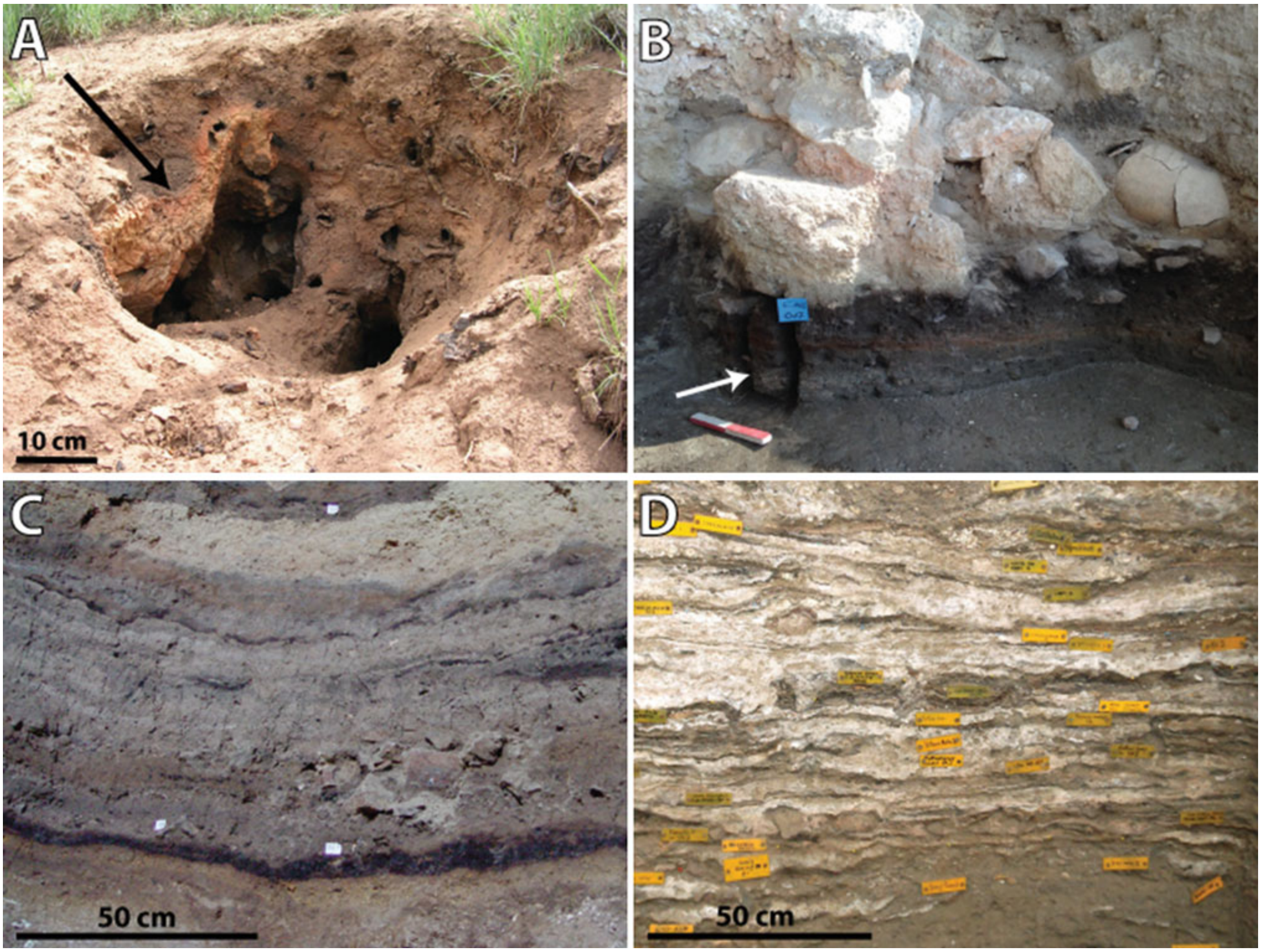
Primary or intact combustion features are located in the place where burning originally occurred, with complete or partial preservation of the original structure and internal spatial arrangement of components. An uncontained primary combustion feature (Figure 1) is a specific type of intact feature that lacks architectural elements and can result from natural processes as well as controlled and uncontrolled use of fire by humans. The lateral spread of burned materials in uncontained primary combustion features may be constrained by the initial distribution of fuel, and their wide extent can blur the boundary between what archaeologists may term features (spatially limited areas) and layers (deposits covering a wider area).

Uncontained primary features include non-anthropogenic fire deposits, such as the remnants of forest and brush fires (Figure 1a), burned materials derived from lightning strikes of trees or tree stumps, or spontaneous ignition of dung or guano. Although they are unrelated to human activity, each of these types of feature may be found in archaeological sites (Bellomo, 1993). Fire destruction layers (conflagrations) result from uncontained burning of single or multiple structures (Figure 1b), often in an urban setting (e.g., Shoval et al., 1989; Namdar et al., 2011). The ignition can be anthropogenic or non-anthropogenic, the former accidental or intentional.

Anthropogenic uncontained primary features can result from intentional ignition of combustible materials for the purposes of physical and psychological site maintenance, cleaning, or abandonment. *Fumier* (Fr.) is one type of uncontained primary feature that consists of one or more burned deposits of interbedded plant material, fodder, and dung that accumulate within animal pens and caves used as stables (Figure 1c; see also Brochier, 1996). Similar behaviors can produce burned bedding or other forms of prepared anthropogenic surfaces (Figure 1d; Goldberg et al., 2009). Finally, deposits associated with ritual closures of structures can include burned materials (e.g., Verhoeven, 2000; Rojo-Guerra et al., 2010; Van Keuren and Roos, 2013).

Contained intact combustion features (Figure 2) result from controlled burning activities in a spatially limited area. The lateral control of combustion, or containment, can be accomplished in a variety of ways ranging from simple placement of fuel to construction of architectural elements. Open hearths are the simplest forms of contained intact combustion features, consisting of unprepared or minimally prepared surfaces composed of the available substrate (Figure 2a). *Cuvettes* (from "en cuvette" Fr.) are a subtype formed on top of shallow depressions. Open hearths are constrained by the lateral distribution of fuel and may be found in association with perimeter lining of stones or banking against one or more preexisting walls.

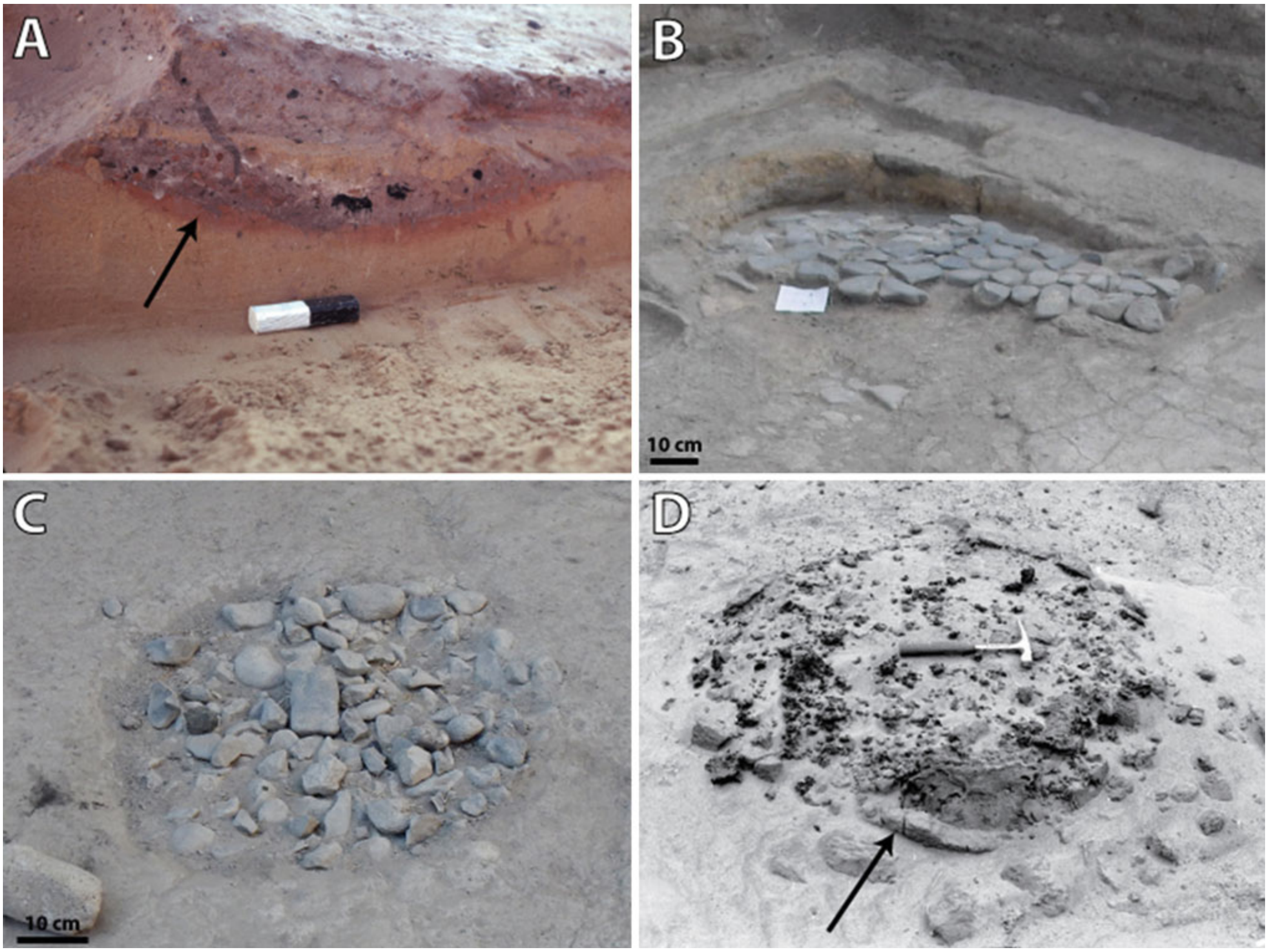
Prepared burning surfaces are a second type of contained intact combustion feature. These features exhibit anthropogenic substrates, such as nonlocal clay, pebbles, flat stones, or plaster (Figure 2b). The substrate may serve to reflect or retain heat, for example, in griddles or braziers. The substrate may also provide a visual focus for activity or serve in the broader construction of space, as in flat altars or platform hearths. A physically durable anthropogenic substrate may also aid in the reuse of the surface (Homsey and Capo, 2006), because removal of burned residues on natural substrates may over time change the morphology of the feature (Mallol et al., 2007).



Hearths and Combustion Features, Figure 1 Different types of intact uncontained combustion features: (**a**) A non-anthropogenic combustion feature formed from the complete burnout of a ponderosa pine snag during the 2002 Rodeo-Chediski Fire. The rubified sediment (*arrow*) is alluvial soil of Early to Mid-Holocene age. Mogollon Rim area of eastern Arizona, USA (Photograph credit: C. Roos in 2005). Non-anthropogenic combustion features located within archaeological sites can lead to issues of interpretation, including misattribution to human activity and misleading radiocarbon dates (Crombé et al., 2015). (**b**) Early tenth-century BCE destruction at Tel Megiddo, Israel. Section showing a burnt floor, an in situ vessel, and mudbrick collapse. Note the block of oriented sediment carved out for micromorphological analysis (*arrow*) (Courtesy of the Megiddo Expedition, Tel Aviv University). (**c**) *Fumier* layers formed during the Chalcolithic period as a result of periodic burning of layers of herbivore dung in a cave. Many of the layers have been subsequently altered by chemical diagenesis, as evidenced by the presence of phosphate minerals such as taranakite. Paltau Cave, Uzbekistan. (**d**) Burned bedding layers at the Middle Stone Age site of Sibudu, South Africa. These laterally extensive combustion features were identified using micromorphological analyses (Goldberg et al., 2009; Wadley et al., 2011).

Unlike open hearths and prepared burning surfaces, pit structures contain primary features that form when burning occurs below the ground surface (Figure 2c). In these features, the fire, or heated rocks, is contained in three dimensions using only locally available substrate and packing layers. Roasting pits, charcoal pits, earth ovens, and some types of simple kilns fall into this category.

Finally, the most complex types of contained intact combustion feature are fire installations (Figure 2d). These features consist of constructed containers located either above or below the ground surface. The containing elements may include prepared substrates and walls, a ceiling of some kind – either constructed or temporary due to the placement of a cooking pot or lid – and ventilation systems that can function actively or passively. Fire installations include fire places, constructed kilns, ovens, incinerators, and furnaces. Both pit structures and fire installations may reflect a desire on the part of their users to control the temperature, duration, or oxygenation conditions of a fire, and variations in their functional morphology have been investigated using ethnographic and experimental studies (Balkansky et al., 1997; Black and Thoms, 2014).

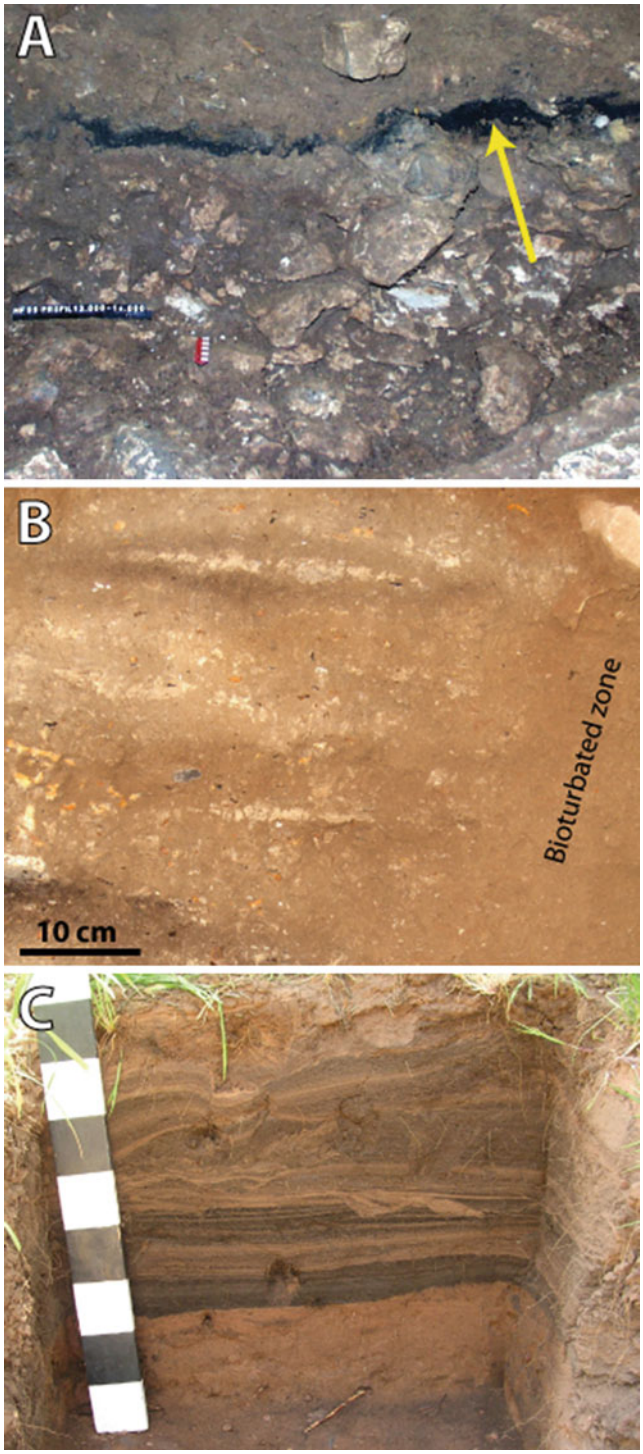


Hearths and Combustion Features, Figure 2 Different types of intact contained combustion features in archaeological sites: (**a**) An Epipaleolithic age open hearth in profile. The substrate is dune sand that has been rubified as a result of heating (*arrow*). The hearth contains visible charcoal and ashes. This stratigraphic sequence of heat-altered substrate overlain by ashes and charcoal is frequently encountered in sections of open hearths. Sinai, Israel (Photograph credit: P. Goldberg). (**b**) A prepared burning surface consisting of flat, rounded cobbles. This feature abuts against two walls of a structure. The surface of this burning surface and similar features was periodically cleaned following burning as evidenced by numerous ash and charcoal layers in middens throughout the site. Neolithic Aşıklı Höyük, Turkey. (**c**) A circular roasting pit filled with fire-cracked rocks and ashes exposed in excavation. Many roasting pits were disturbed in prehistoric times when the features were excavated in order to retrieve their contents following burning. Neolithic Aşıklı Höyük, Turkey. (**d**) A portion of a fire installation exposed by deflation. The feature is the remains of an iron smelting furnace that is filled with slag and fragments of the furnace shaft. Portions of the external walls are visible (*arrow*). The feature was intentionally broken in order to retrieve the bloom after smelting. Middle Senegal River Valley, Senegal (Photograph credit: D. Killick).

In secondary or reworked combustion features, the by-products of burning are not in their original place of combustion but are concentrated in such a way that archaeologists might still define them in the field as a feature. Reworking can result from human activity with the degree of intentionality ranging from trampling to active rake-out, fuel removal, sweeping, dumping (Figure 3a), secondary inhumation of cremations, or deliberate destruction of a feature. Reworking can also result from the feeding and nesting activities of other animals or insects. Bioturbation of burned materials physically moves components laterally or vertically and destroys the original structure and fabric of the feature (Figure 3b), while consumption of burned materials by mesofauna may chemically transform them. Finally, reworking can result from any number of surface processes such as transport by water, wind and gravity (Figure 3c), pedoturbation, and cryogenesis.

Methods

Methods for identification of combustion features and their microscopic components have been reviewed previously by Mentzer (2014). Here, the overview of



Hearths and Combustion Features, Figure 3 Reworked combustion features: (**a**) A Gravettian deposit comprising sand-sized fragments of burned bone in secondary context. The feature, which is expressed in the field as a black lens, is interpreted as a dump (Schiegl et al., 2003) (Photograph credit: M. Malina). (**b**) A sequence of partially bioturbated open hearths in the Middle Paleolithic site of Üçağızlı Cave II, Turkey. The ash layers visible on the *left side* of the photograph have been disturbed by tubular insect burrows. The sediment in between the ash layers contains general occupation debris. The sediment to the *right* is rich in burned materials, but is entirely homogenized by bioturbation. (**c**) Micro-charcoal in postfire erosion deposits that accumulated after the 1974 Day Burn in eastern Arizona, USA. The strongly laminated fabric is typical of deposition by water (Photograph credit: C. Roos).

methodological approaches is expanded to include field-based observations and techniques.

Field methods

Many combustion features and their components are first encountered visually in the field and documented using macroscale observations. Characteristics include the observation of by-products of combustion: concentrations of charcoal or charred plant material; gray, silty sediment; patches of sediment that are dark or rubified; and concentrations of other heated materials such as bone and slag. However, many researchers have noted that visual observations or identification of the by-products of combustion alone are not reliable on their own (e.g., Stahlschmidt et al., 2015). For example, it is possible to mistake humified plant tissues for charcoal under field observation conditions. Gray, silty sediment does not always derive its characteristics from the presence of calcareous ashes. Redoximorphic processes can produce patches of dark or rubified sediment, and sediment color changes with heating are highly variable (Canti and Linford, 2000). Finally, postdepositional staining can cause bone fragments to appear burned (Shahack-Gross et al., 1997). Therefore, all field-based documentation and identification of burned materials should be confirmed using laboratory analyses.

Other aspects of combustion features may also be identified visually. These include architectural elements of prepared burning surfaces and fire installations. In these cases, visual identification can be quite reliable in the field when the architectural features are distinctive (see Figure 2d). However, other types of feature can be more ambiguous. For example, simple rings of stones are not the best evidence for the former presence of a hearth, as humans produce concentrations of stones while conducting other activities.

Geoarchaeologists may conduct certain analyses while working in the field (Figure 4) directly on the combustion feature or on subsamples recovered during excavation or in profiles. Grain mount analysis (Figure 4a) is a simple petrographic method that can be used to distinguish calcareous wood ashes from other sources of gray, silty sediment at archaeological sites (see also Mentzer, 2014; Figure 2). This approach requires a portable petrographic microscope, as well as glass slides and a mounting medium. Grain mount analysis can also be used to identify or quantify other microscopic components of ashes that are indicative of fuel source, such as calcareous spherulites and phytoliths that derive from dung (Gur-Arieh et al., 2013).

On-site geochemical methods can also be used to identify specific types of burned materials. Hydrochloric acid produces carbon dioxide when exposed to calcareous minerals, some of which may be present in combustion features. The positive reaction of gray, silty sediment with hydrochloric acid can strengthen a working hypothesis that the purported combustion feature contains calcareous ashes. This approach must be used cautiously because the presence of other sources of silty calcareous materials (e.g., loess, dung spherulites) can result in a false-positive result.

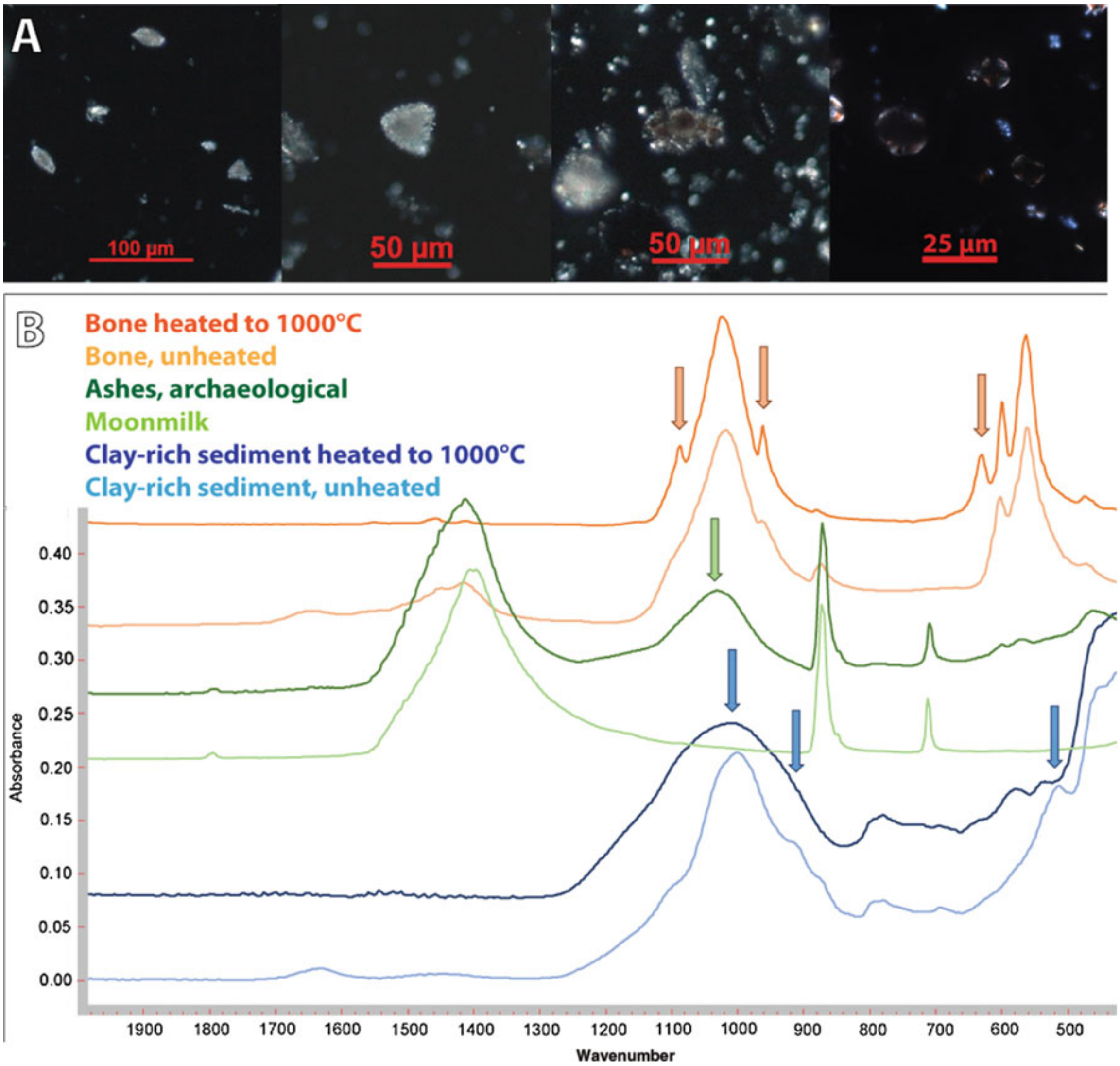
Another mineralogical method is Fourier transform infrared spectroscopy (FTIR) (Figure 4b). Analyses of loose subsamples of sediment can be conducted using a portable instrument in a field laboratory in order to study a variety of components, including calcite in suspected ashy sediment (Schiegl et al., 1996). Furthermore, the technique can be used to distinguish pyrogenic sources of calcite from geogenic and biogenic sources (Regev et al., 2010) and to identify burned bone and reconstruct burning temperatures (Thompson et al., 2013).

Certain types of magnetic methods can be conducted on site, prior to, or during excavation while others require specialized laboratory equipment (Bellomo, 1993). Magnetometry involves the use of on-site measurements of fluctuations in the local magnetic field to identify the presence of buried features that are enriched in ferromagnetic minerals and other substances. Magnetometry can also be used to identify localities where burning may have taken place or where heated materials have been redeposited and are apparent due to their acquired thermoremanent magnetism. Remnant magnetism is the measurement of the direction and strength of the local magnetic field at the last time that ferromagnetic minerals were cooled after heating within a combustion feature. This approach can be used to determine if materials were heated at any time in the past, with further parameters used for dating purposes or to reconstruct the local magnetic field (see below).

Magnetic susceptibility measurements of the abundance of magnetized grains in sediment can be conducted in the field or laboratory. Magnetic susceptibility can increase in sediments that have been exposed to heat due to the formation of ferromagnetic minerals, such as magnetite and maghemite, from weakly paramagnetic compounds that are initially present in most types of sediment (Jordanova et al., 2001). Because magnetic susceptibility can also increase due to soil-forming processes, integration with other methods or a careful study of the spatial distribution of susceptible sediments must be conducted (e.g., Herries and Fisher, 2010).

Laboratory methods

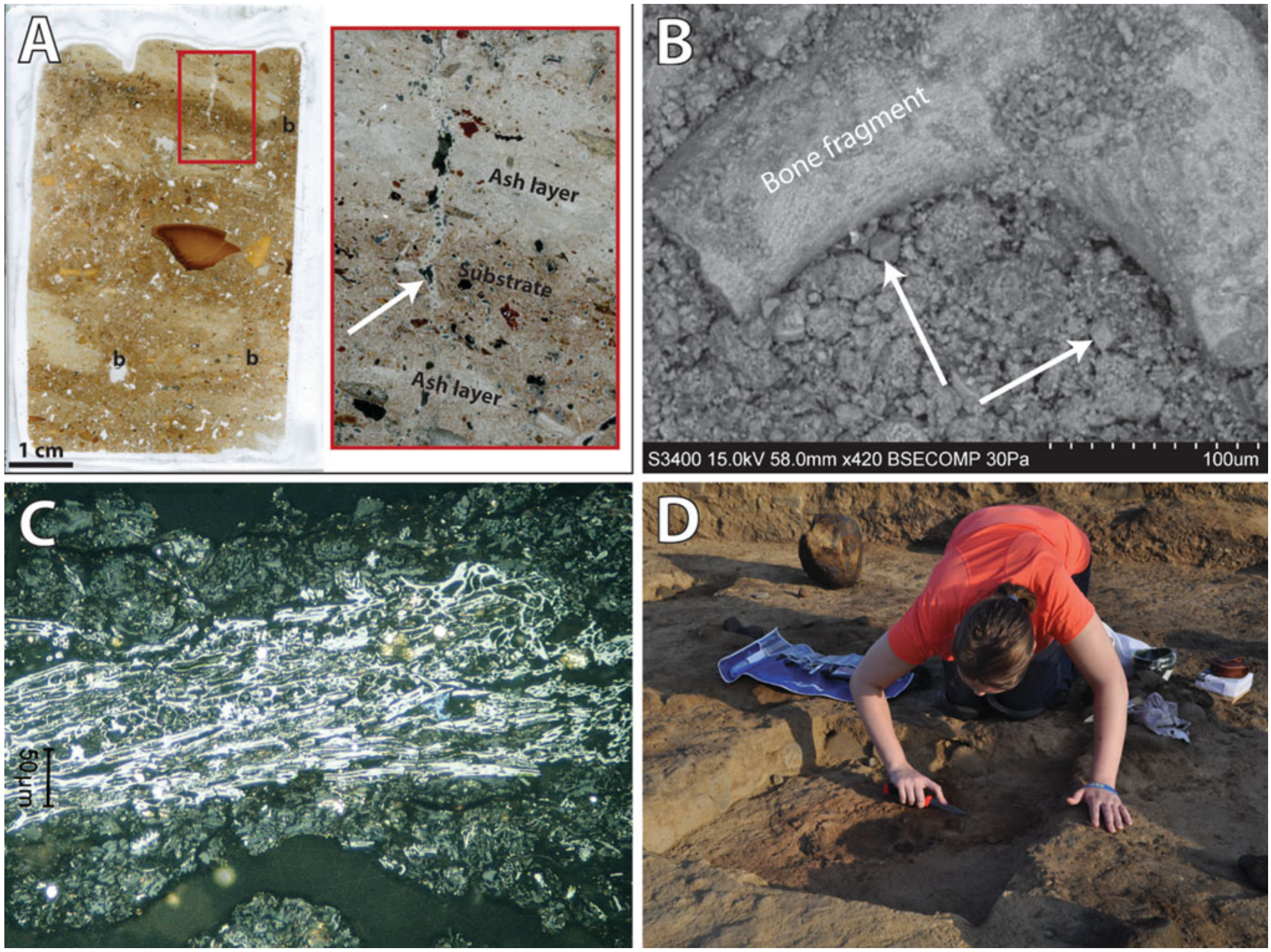
Field analyses of combustion features are typically followed by laboratory analyses of specific components (Figure 5). Micromorphology is a laboratory-based approach in which intact and oriented blocks of archaeological sediment are hardened with the aid of impregnation resin, sliced, and prepared into polished blocks and/or petrographic thin sections (Figure 5a). The prepared sections are then studied at magnification using a variety of instruments including, but not limited to, petrographic microscopes (Courty et al., 1989). This technique, which utilizes only a subsample of the larger feature, allows for the identification of anthropogenic, geogenic, and biogenic



Hearths and Combustion Features, Figure 4 Field analytical methods: (**a**) Examples of fuel residues identified using grain mounts under cross-polarized light. From *left* to *right*: experimental wood ashes produced from *Aesculus hippocastanum* (horse chestnut) burned for 4 h at 400 °C, archaeologically recovered wood ashes, experimentally heated dung spherulites burned for 1 h at 600 °C, archaeologically heated dung spherulites. Depending on available supplies, grain mounts or smear slides may be produced and analyzed quickly using glass slides and a mounting medium, with or without a cover slip. The experimental spherulite sample was prepared with Entellan new mounting medium and a cover slip. The remaining samples were prepared with paraffin lamp oil. The archaeological samples are from the combustion features in Figure 6a. (**b**) Fourier transform infrared spectroscopy-attenuated total reflectance (FTIR-ATR) spectra of typical components of combustion features compared to their unheated counterparts. The arrows indicate the positions of characteristic peaks that appear in heated materials. In the ash sample, the characteristic peak indicates the presence of silica from clay and phytoliths. These analyses can be conducted in the field using a portable spectrometer, and they can aid in the identification of fuel residues, heated materials, and feature substrates.

components using optical properties. Micromorphology is especially useful for the identification of burned materials, such as ashes (Canti, 2003; Shahack-Gross and Ayalon, 2013), bone, and shell (Villagran, 2014). The technique also facilitates description of the spatial distribution of components as well as documentation of internal structures and fabrics. These characteristics are critical for assessing whether features are primary or secondary and whether burned components have been impacted by physical and chemical taphonomic processes. In many cases, micromorphological analyses yield a wealth of information about human choices in fuel selection, construction and maintenance of the feature during its use, discard practices, and postdepositional alterations (Mentzer, 2014).

Other high-resolution laboratory analyses include scanning electron microscopy, which can yield information



Hearths and Combustion Features, Figure 5 Laboratory analytical methods: (**a**) Micromorphology is a common laboratory technique for the study of combustion features. Here, an incident light scan of a micromorphological thin section from the features illustrated in Figure 3b contains several open hearths. Insect burrows (**b**) are visible in the ash layer of a lower hearth. Two additional hearths are present at the *top* of the sample, and a higher magnification view under cross-polarized light (*inset*) reveals that the two ash layers are separated by a thin anthropogenic deposit that forms the substrate for the uppermost hearth. A crack void (*arrow*) is infilled with secondary carbonate. (**b**) Scanning electron microscopy can be used to image combustion feature components at very high magnification or measure elemental abundances. Wood ashes (*arrow*) and a sand-sized fragment of burned bone are visible in a loose sediment sample from the sacrificial ash at the altar to Zeus on Mt. Lykaion, Greece (see also Mentzer et al., 2015). This image of the particle morphology and surface topography was generated using the secondary electron detector. (**c**) Photomicrograph from an analysis of peat using organic petrology (oil immersion, reflected *white light*). The highly reflective material in the *center* of the image is fusinite in a fragment of charcoal derived from a natural fire and redeposited by wind or stream flow. The fusinite shows slight compression from compaction of the peat. The surrounding porous matrix is humified plant detritus which appears *dark gray*. Pleistocene peat level 13-II-3 from Schöningen, Germany (Photograph credit: D. Liguois). (**d**) Combustion features and their contents can be dated using a variety of methods, including radiocarbon, TL, OSL and archaeomagnetic dating. Here, a researcher collects a sample for archaeomagnetic analysis from the site of Pampas Gramalote, Peru. In this process, intact hearths are excavated to yield small, oriented blocks of sediment, which are secured inside a brass mold using clay and plaster. An azimuth is measured, and the exact location of the measurement is marked in the wet plaster. The molds prevent shifting of the sediment from its original position with respect to the measurement mark. In the laboratory, the researcher will measure the thermal remanent magnetism and calculate the magnetic declination at the time of burning. The results will be compared to a regional secular variation curve to obtain the age of the feature (Photograph credit: G. Prieto).

about the elemental composition of materials as well as morphological properties, such as observation of the presence of rhombic aggregates of microcrystalline carbonate that are characteristic of wood ashes (Figure 5b; see also Shahack-Gross and Ayalon, 2013). Organic petrology is an analytical approach that was developed for the study of coal, but that has applications in the study of combustion features. Reflectance measurements conducted on polished materials mounted in resin can be used to distinguish charcoal and charred plant material from humified plant material (Stahlschmidt et al., 2015). Similar measurements can also identify gels and fat-derived char that result from the heating of other materials (Figure 5c; also Goldberg et al., 2009).

Laboratory-based mineralogical methods include FTIR, which can be conducted on loose samples to address the same research questions as above. Additional applications of FTIR include reconstructing temperatures of heated sediment, which requires laboratory-based heating experiments using local sediment for calibration purposes (Berna et al., 2007; Forget et al., 2015). FTIR microspectroscopy entails the identification of heated materials in thin section or polished sediment block (Goldberg and Berna, 2010), and the approach combines the spatial information of a micromorphological analysis with molecular and optical identification of materials. Like FTIR, X-ray diffraction (XRD) can be used to identify calcite in purported ashes, as well as changes to the crystal structure of bone that result from heating (Rogers and Daniels, 2002).

Finally, other methods include elemental and isotopic geochemical analyses and luminescence measurements. Multielement mapping and analyses of the relative abundance of carbonates and plant-available phosphorus can be used to identify enrichments to archaeological sediments that result from burning (Wilson et al., 2008). Isotopic methods include measurements of the stable isotopes of oxygen and carbon in calcareous materials. This approach can yield ratios that are characteristic of calcareous ashes in various states of secondary cementation (Shahack-Gross et al., 2008; Shahack-Gross and Ayalon, 2013) when other properties of the materials, such as morphology, have been modified by postdepositional processes.

Luminescence methods include electron spin resonance (ESR), thermoluminescence (TL), and optically stimulated luminescence (OSL). ESR measurements can be conducted on bone and charred plant materials to determine the temperature of heating (Hillman et al., 1985; Hayes and Shurr, 2002). TL measurements can be taken on heated rocks (Richter, 2007), and OSL measurements can be conducted on rocks or quartz grains within architectural components using the quartz inclusion technique (Fleming, 1970; Murray and Mejdahl, 1999) or directly on the heated substrate (Rhodes et al., 2010). Both approaches depend upon the fact that heating empties electron traps within the target material. Following this reset, the radiation dose received over time excites additional electrons which accumulate within traps in the material and thereby provide a means to calculate the time of heating. Exploiting these techniques and applications of the radiocarbon method to charcoal and calcined bone, combustion features, and their contents can contribute to the dating of an archaeological site.

The choice of methods in the study of combustion features is determined by a number of factors, including access to on-site instrumentation, budget, ability to subsample and remove portions of the feature to a laboratory setting, and ultimate research questions. All methods are appropriate for identifying one or more by-products of combustion, but not all methods are appropriate for determining whether the features were generated by people. The strongest approaches are those that are integrative (Figure 6). The microcontextual approach (Goldberg and Berna, 2010) utilizes different types of petrographic analyses and microsampling within micromorphological sediment blocks. This approach can facilitate the direct comparison of the results of micromorphology, organic petrology, mineralogical analyses, and isotopic measurements (Figure 6a).

Approaches to the interpretation of combustion features

Geoarchaeological analyses of combustion features contribute to understanding the formation processes of features and archaeological sites. For example, a micromorphological study of a suspected hearth might reveal evidence for postdepositional processes, such as decalcification or bioturbation, that could have also impacted the preservation and distribution of other archaeological materials in the site. More importantly, geoarchaeological analyses of combustion features can provide a means to answer a wide variety of research questions about human activity in the past.

At the site scale, geoarchaeologists might ask:

- What is this feature?
- Was the burning a result of human activity?
- What types of fuels were used in domestic and nondomestic contexts?
- How were hearths, ovens, and kilns constructed with respect to other architectural elements?
- Where were wastes dumped at the site?

At larger scales, geoarchaeologists can help address questions, such as:

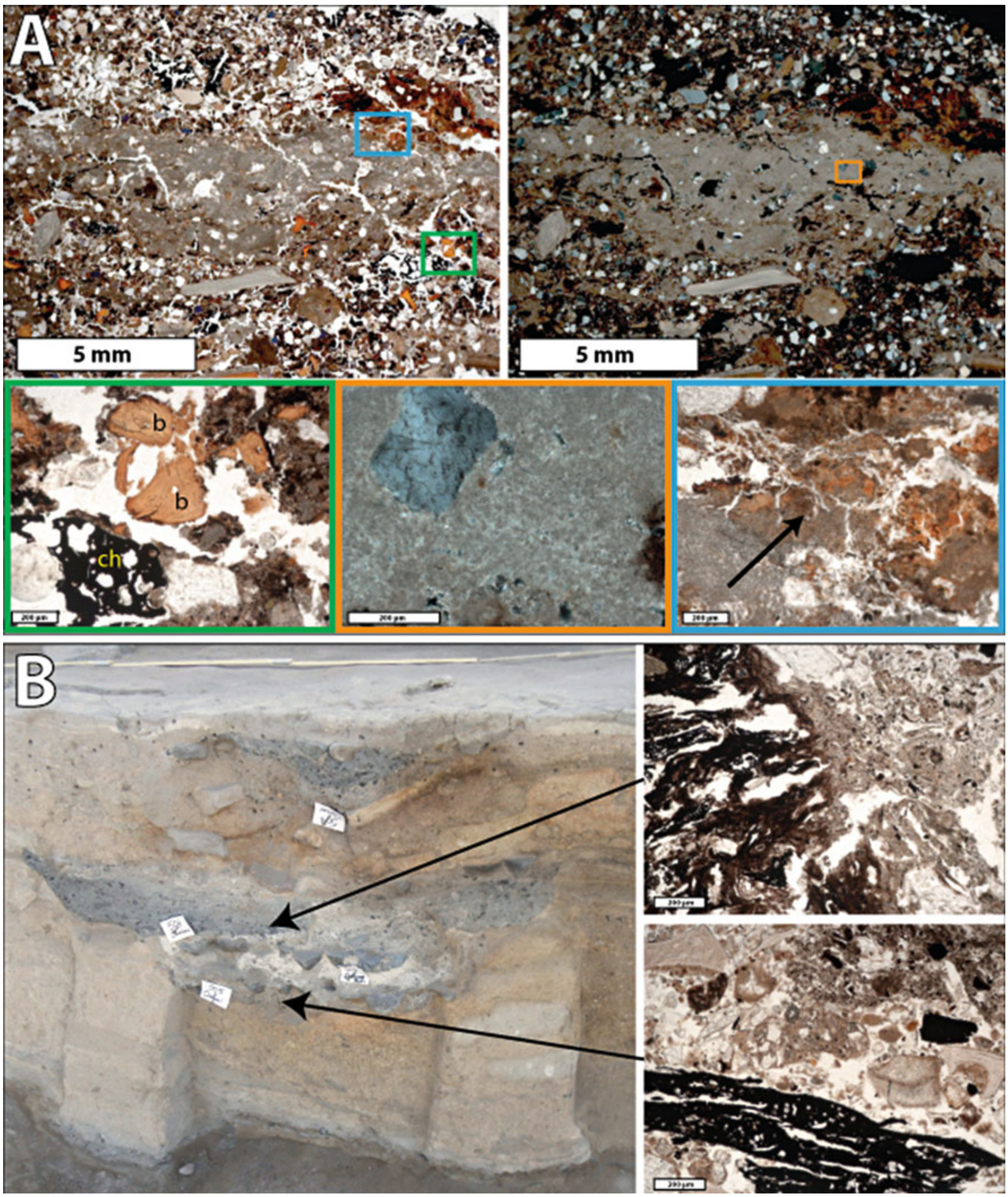
- Are there regional changes in intensity of site use?
- Did fuel availability change over time?
- How did humans use fire to manage their landscapes?
- Who had access to different types of pyrotechnology?
- Where did fire sacrifice originate and how did it spread throughout the region?

The following section provides an overview of some current research themes pertaining to fire and pyrotechnology and ways in which geoarchaeologists are contributing to their study.

Controlled use of fire

Fire use, habitual fire use, and controlled use of fire are considered by many to be key developments in hominin behavioral evolution. For example, fire use for cooking may have facilitated physical changes in hominin cognition (Wrangham et al., 1999). Fire use may have allowed hominins to colonize or exploit new environments, and some argue that regular access to fire was a trait that distinguished humans from Neanderthals (Sandgathe et al., 2011). As a first step toward testing these hypotheses, archaeologists must be able to identify definitely materials that have been burned. Furthermore, researchers such as James (1989) call for a critical evaluation of the evidence for hominin control of fire, noting that it is imperative that archaeologists distinguish between combustion features that formed as a result of hominin activity and those that may have formed from natural processes.

Most recently, Roebroeks and Villa (2011) reiterate that burned materials alone are not evidence for human agency in the presence of fire at an archaeological site. Instead, they argue that archaeologists must address the



Hearths and Combustion Features, Figure 6 (Continued) relationship between the burned materials and the broader archaeological context. In considering early evidence for fire in Europe, Roebroeks and Villa state that certain analytical methods are more reliable than others. In particular, they rank evidence for early fire at different sites using an "index of confidence" that is based on whether isolated burned materials or combustion features were identified and how the latter were studied. Sites that Roebroeks and Villa assign to the highest confidence index (i.e., a rank of 3) contain combustion features that were documented either using micromorphology or multiple geoarchaeological techniques. Applying similar criteria on a global scale, some claims for early fire at Lower Paleolithic sites such as Zhoukoudian and Swartkrans would not earn high indices. However, some cases for Lower Paleolithic fire are more robust (e.g., Gesher Benot Ya'aqov; see Alperson-Afil et al., 2007), and at the time of writing, geoarchaeologists working at Qesem Cave (Israel) have provided a convincing case for controlled and repeated use of fire in the Late Lower Paleolithic. Karkanas et al. (2007) and Shahack-Gross et al. (2014) integrate micromorphology of combustion features with isotopic and mineralogical analyses of the ashes contained therein.

Paleosurfaces versus palimpsests

Identification of combustion features can also contribute to debates regarding the distinction between so-called living floors and time-averaged accumulations of materials in archaeological sites (Dibble et al., 1997; Bailey, 2007; Malinsky-Buller et al., 2011). In sites lacking architecture, combustion features can mark the level of an ancient surface (Mentzer, 2014). Single burning events rarely last longer than days or weeks, and depending on their morphology, the resulting combustion features can provide information about the morphology and level of the ground during specific moments in time, or they may even protect underlying deposits from reworking due to human or animal activity (see Figures 1c and 3c). Geoarchaeological studies of multicomponent features, such as the stacked and reused hearth sequences at Kebara Cave or the destruction layer at Tel Dor (Berna et al., 2007), can also be used to provide information about rates of sedimentation within the site.

Organization and maintenance of space and local environment

In archaeological sites, the spatial relationship between combustion features and the physical traces of other activities can help researchers to understand the human organization of space. Geoarchaeological analyses of features can contribute to understanding whether spaces were areas of primary activity (e.g., hearths) or peripheral zones (e.g., middens) (e.g., Kebara Cave). The duration of use of these features can also yield clues to understanding social memory. Likewise, evidence for investment in the production of burning surfaces or installations can be informative about the intensity of occupation and residential permanence. In large sites, the morphology of combustion features and their locations with respect to traces of domestic and nondomestic activities can inform archaeologists about functional diversification of fire and ancient pyrotechnology.

The destructive properties of fire were harnessed by ancient people for both physical and psychological purposes. For example, the periodic burning of anthropogenic ground surface coverings (bedding) has been identified using micromorphology in sites as old as the Middle Stone Age (see Figure 1d; Goldberg et al., 2009). Wadley et al. (2011) postulate that this repeated maintenance behavior could indicate a desire by the inhabitants of the site of Sibudu to rid their domestic space of wastes and insects. In some pastoral sites, periodic burning of layers of dung and fodder was conducted on an annual or semiannual basis in order to rejuvenate stabling areas (see Figure 1c). Researchers postulate that this behavior served

Hearths and Combustion Features, Figure 6 Integrative methods in the study of combustion features: (**a**) The micro-contextual approach uses the micromorphological sample as the main unit of analysis (Goldberg and Berna, 2010). Geochemical analyses are conducted directly on the thin section, on the resin-impregnated sediment block, or on sediment drilled from the resin-impregnated block. In the open hearth pictured here (*right*, under plane polarized light; *left*, under cross-polarized light), three areas (***colored boxes***) will be targeted for geochemical analysis. First, organic petrology and micro-FTIR analyses will be conducted on the char (ch) and bone fragments (**b**) in order to identify their source and burning temperature (see Goldberg et al., 2009; Thompson et al., 2013). Second, isotopic analyses will be conducted on micro-drilled powders of the microcrystalline carbonate in order to confirm the petrographic identification of cemented ashes (see Shahack-Gross et al., 2008; Mentzer and Quade, 2013; Shahack-Gross and Ayalon, 2013). Finally, micro-FTIR analyses will be conducted on the *yellow* upper surface of the ash layer (*arrow*) to identify the presence of secondary phosphate minerals and reconstruct the postdepositional chemical alteration of the feature (see Schiegl et al., 1996). Klasies River Mouth, South Africa. (**b**) Radiocarbon dating may be coupled with micromorphological analyses of combustion features in order to provide context for the samples to be dated (see Toffolo et al., 2012). A sequence of up to eight combustion features are visible in the profile on the *left*. Their field identifications are based on the presence of visible charcoal fragments and sediment that appears ashy. Several of the features have prepared burning surfaces, while others are *en cuvette*. Two radiocarbon samples are matched with micromorphological analyses (*arrows*). The context for the upper sample is more secure. The fuel can be identified as dung, which is composed of short-lived plant parts, and the structure of the sample reveals little postdepositional disturbance. In contrast, the lower sample contains charcoal in a matrix of other anthropogenic materials, which raises the possibility that the burned materials could be in secondary context. Aşıklı Höyük, Turkey.

to reduce the volume of sediment in constrained spaces (e.g., caves) and also minimized insect populations. Redeposited ashes may have also served similar purposes, with their alkaline properties contributing to pest management or their symbolic purity serving to rejuvenate a space (Hakbijl, 2002). Destruction layers and ritual closure may likewise evidence the use of fire as a tool of psychological destruction. Finally, beyond the scale of the archaeological site, fire was used as a tool for managing landscapes (Conedera et al., 2009; Bowman et al., 2011). Geoarchaeological analyses of modern and experimental forest fire residues are currently contributing to the understanding of ancient land use practices (Rösch et al., 2002; Eckmeier et al., 2007; Roos, 2008).

Other uses of combustion features

Combustion features in archaeological sites possess significance beyond their relationships to past human activities, as they provide materials that are suitable for dating and paleoenvironmental reconstruction.

In sites that are younger than ~45,000 years, radiocarbon measurements can be conducted on charcoal and charred plant material. Less commonly, calcined bone fragments (Lanting et al., 2001) and ashes may also be dated, but their apparent ages relative to the burning event are complicated by the temperature of combustion as well as postdepositional processes (Regev et al., 2011). In radiocarbon dating, integrative approaches are increasingly being favored, such that sampling localities are documented at high-resolution and assessed for evidence of reworking or other taphonomic factors (Figure 6b; Toffolo et al., 2012). Combustion features can also provide materials suitable for dating using luminescence methods: either TL on heated rock (Richter, 2007) or OSL measurements on heated substrates or mineral inclusions within architectural features (Fleming, 1970; Rhodes et al., 2010). Finally, measurements of thermoremanent magnetism, or archaeomagnetic dating, can be used in conjunction with reconstructions of past magnetic fields to date the most recent burning event within a combustion feature (Figure 5d) (Eighmy and Sternberg, 1990). Sampling prioritizes portions of the feature associated with the substrate, such as rocks used in linings or as paving, or the floors of installations. In these cases, geoarchaeological techniques can be used to establish that heated materials have not moved since the last firing. Conversely, the fuels inside combustion features may be dated using radiometric methods, and measurements of thermal remnant magnetism conducted on the substrates may be used to identify and date fluctuations in the local magnetic field. Kapper et al. (2014) stress that these types of studies together with micromorphology can aid in identifying appropriate samples.

Combustion features can also provide materials that are useful for paleoenvironmental reconstruction. Botanical analysis of charcoal and other types of charred plant materials in combustion features can be identified as to plant part and sometimes to genus or species. Phytolith analyses may be conducted on the siliceous portion of plant ashes (see Figure 6b; also Albert et al., 2012). If geoarchaeological analyses support the interpretation that combustion features were produced by human activity, botanical and phytolith analyses can be used to reconstruct fuel choices in the past. Although fuel choice may be motivated by desired properties of the fire (Théry-Parisot, 2002), it can also reflect availability of plants in the local environment (Asouti and Austin, 2005).

Conclusions

As outlined above, geoarchaeological analyses are becoming essential tools for the identification and interpretation of combustion features in archaeological sites of all ages. This growing area of focus encourages integrative approaches, wherein geoarchaeologists employ a variety of field- and laboratory-based methods to identify the traces and composition of burned materials, as well as understand their relationship to past human activities. Combustion feature research can be conducted at many scales: from micromorphological analyses of individual burning events to landscape-scale records of forest clearance. Furthermore, in studying combustion features, geoarchaeologists are actively engaged in the research and interpretation of sediments as artifacts, an approach which requires us ultimately to ask and answer anthropological – as opposed to geological – questions.

Bibliography

Albert, R. M., Berna, F., and Goldberg, P., 2012. Insights on Neanderthal fire use at Kebara Cave (Israel) through high resolution study of prehistoric combustion features: evidence from phytoliths and thin sections. *Quaternary International*, **247**, 278–293.

Alperson-Afil, N., Richter, D., and Goren-Inbar, N., 2007. Phantom hearths and the use of fire at Gesher Benot Ya'aqov, Israel. *PaleoAnthropology* 1–15.

Asouti, E., and Austin, P., 2005. Reconstructing woodland vegetation and its exploitation by past societies, based on the analysis and interpretation of archaeological wood charcoal macro-remains. *Environmental Archaeology*, **10**(1), 1–18.

Bailey, G., 2007. Time perspectives, palimpsests and the archaeology of time. *Journal of Anthropological Archaeology*, **26**(2), 198–223.

Balkansky, A. K., Feinman, G. M., and Nicholas, L. M., 1997. Pottery kilns of ancient Ejutla, Oaxaca, Mexico. *Journal of Field Archaeology*, **24**(2), 139–160.

Bellomo, R. V., 1993. A methodological approach for identifying archaeological evidence of fire resulting from human activities. *Journal of Archaeological Science*, **20**(5), 525–553.

Berna, F., Behar, A., Shahack-Gross, R., Berg, J., Boaretto, E., Gilboa, A., Sharon, I., Shalev, S., Shilstein, S., Yahalom-Mack, N., Zorn, J. R., and Weiner, S., 2007. Sediments exposed to high temperatures: reconstructing pyrotechnological processes in Late Bronze and Iron Age Strata at Tel Dor (Israel). *Journal of Archaeological Science*, **34**(3), 358–373.

Black, S. L., and Thoms, A. V., 2014. Hunter-gatherer earth ovens in the archaeological record: fundamental concepts. *American Antiquity*, **79**(2), 204–226.

Bowman, D. M. J. S., Balch, J., Artaxo, P., Bond, W. J., Cochrane, M. A., D'Antonio, C. M., DeFries, R., Johnston, F. H., Keeley, J. E., Krawchuk, M. A., Kull, C. A., Mack, M., Moritz, M. A., Pyne, S., Roos, C. I., Scott, A. C., Sodhi, N. S., and Swetnam, T. W., 2011. The human dimension of fire regimes on Earth. *Journal of Biogeography*, **38**(12), 2223–2236.

Brochier, J. E., 1996. Feuilles ou fumiers? Observations sur le rôle des poussières sphérolitiques dans l'interprétation des dépôts archéologiques holocènes. *Anthropozoologica*, **24**, 19–30.

Canti, M. G., 2003. Aspects of the chemical and microscopic characteristics of plant ashes found in archaeological soils. *Catena*, **54**(3), 339–361.

Canti, M. G., and Linford, N., 2000. The effects of fire on archaeological soils and sediments: temperature and colour relationships. *Proceedings of the Prehistoric Society*, **66**, 385–395.

Conedera, M., Tinner, W., Neff, C., Meurer, M., Dickens, A. F., and Krebs, P., 2009. Reconstructing past fire regimes: methods, applications, and relevance to fire management and conservation. *Quaternary Science Reviews*, **28**(5–6), 555–576.

Courty, M. A., Goldberg, P., and Macphail, R. I., 1989. *Soils and Micromorphology in Archaeology*. Cambridge: Cambridge University Press.

Crombé, P., Langohr, R., and Louwagie, G., 2015. Mesolithic hearth-pits: fact or fantasy? A reassessment based on the evidence from the sites of Doel and Verrebroek (Belgium). *Journal of Archaeological Science*, **61**, 158–171.

Dibble, H. L., Chase, P. G., McPherron, S. P., and Tuffreau, A., 1997. Testing the reality of a" living floor" with archaeological data. *American Antiquity*, **62**(4), 629–651.

Eckmeier, E., Gerlach, R., Skjemstad, J. O., Ehrmann, O., and Schmidt, M. W. I., 2007. Minor changes in soil organic carbon and charcoal concentrations detected in a temperate deciduous forest a year after an experimental slash-and-burn. *Biogeosciences*, **4**(3), 377–383.

Eighmy, J. L., and Sternberg, R. S. (eds.), 1990. *Archaeomagnetic Dating*. Tucson: University of Arizona Press.

Fleming, S. J., 1970. Thermoluminescent dating: refinement of the quartz inclusion method. *Archaeometry*, **12**(2), 133–143.

Forget, M. C. L., Regev, L., Friesem, D. E., and Shahack-Gross, R., 2015. Physical and mineralogical properties of experimentally heated chaff-tempered mud bricks: implications for reconstruction of environmental factors influencing the appearance of mud bricks in archaeological conflagration events. *Journal of Archaeological Science: Reports*, **2**, 80–93.

Goldberg, P., and Berna, F., 2010. Micromorphology and context. *Quaternary International*, **214**(1–2), 56–62.

Goldberg, P., Miller, C. E., Schiegl, S., Ligouis, B., Berna, F., Conard, N. J., and Wadley, L., 2009. Bedding, hearths, and site maintenance in the Middle Stone age of Sibudu cave, KwaZulu-Natal, South Africa. *Archaeological and Anthropological Sciences*, **1**(2), 95–122.

Gur-Arieh, S., Mintz, E., Boaretto, E., and Shahack-Gross, R., 2013. An ethnoarchaeological study of cooking installations in rural Uzbekistan: development of a new method for identification of fuel sources. *Journal of Archaeological Science*, **40**(12), 4331–4347.

Hakbijl, T., 2002. The traditional, historical and prehistoric use of ashes as an insecticide, with an experimental study on the insecticidal efficacy of washed ash. *Environmental Archaeology*, **7**(1), 13–22.

Hayes, R. G., and Schurr, M. R., 2002. Electron spin resonance studies to explore the thermal history of archaeological objects. In Jakes, K. A. (ed.), *Archaeological Chemistry: Materials, Methods, and Meaning*. Washington, DC: American Chemical Society. ACS Symposium Series, Vol. 831, pp. 151–168.

Herries, A. I., and Fisher, E. C., 2010. Multidimensional GIS modeling of magnetic mineralogy as a proxy for fire use and spatial patterning: evidence from the Middle Stone Age bearing sea cave of Pinnacle Point 13B (Western Cape, South Africa). *Journal of Human Evolution*, **59**(3–4), 306–320.

Hillman, G. C., Robins, G. V., Oduwole, D., Sales, K. D., and McNeil, D. A. C., 1985. The use of electron spin resonance spectroscopy to determine the thermal histories of cereal grains. *Journal of Archaeological Science*, **12**(1), 49–58.

Homsey, L. K., and Capo, R. C., 2006. Integrating geochemistry and micromorphology to interpret feature use at Dust Cave, a Paleo-Indian through middle-archaic site in Northwest Alabama. *Geoarchaeology*, **21**(3), 237–269.

James, S. R. 1989. Hominid use of fire in the Lower and Middle Pleistocene: A review of the evidence. *Current Anthropology*, 1–26.

James, S. R., Dennell, R. W., Gilbert, A. S., Lewis, H. T., Gowlett, J. A. J., Lynch, T. F., McGrew, W. C., Peters, C. R., Pope, G. G., Stahl, A. B., and James, S. R., 1989. Hominid use of fire in the Lower and Middle Pleistocene: a review of the evidence [and comments and replies]. *Current Anthropology*, **30**(1), 1–26.

Jordanova, N., Petrovsky, E., Kovacheva, M., and Jordanova, D., 2001. Factors determining magnetic enhancement of burnt clay from archaeological sites. *Journal of Archaeological Science*, **28**(11), 1137–1148.

Kapper, K. L., Anesin, D., Donadini, F., Angelucci, D. E., Cavulli, F., Pedrotti, A., and Hirt, A. M., 2014. Linking site formation processes to magnetic properties. Rock- and archeomagnetic analysis of the combustion levels at Riparo Gaban (Italy). *Journal of Archaeological Science*, **41**, 836–855.

Karkanas, P., Shahack-Gross, R., Ayalon, A., Bar-Matthews, M., Barkai, R., Frumkin, A., Gopher, A., and Stiner, M. C., 2007. Evidence for habitual use of fire at the end of the Lower Paleolithic: site-formation processes at Qesem Cave, Israel. *Journal of Human Evolution*, **53**(2), 197–212.

Lanting, J. N., Aerts-Bijma, A. T., and van der Plicht, J., 2001. Dating of cremated bones. *Radiocarbon*, **43**(2A), 249–254.

Malinsky-Buller, A., Hovers, E., and Marder, O., 2011. Making time: 'Living floors', 'palimpsests' and site formation processes – a perspective from the open-air Lower Paleolithic site of Revadim Quarry, Israel. *Journal of Anthropological Archaeology*, **30**(2), 89–101.

Mallol, C., Marlowe, F. W., Wood, B. M., and Porter, C. C., 2007. Earth, wind, and fire: ethnoarchaeological signals of Hadza fires. *Journal of Archaeological Science*, **34**(12), 2035–2052.

Mentzer, S. M., 2014. Microarchaeological approaches to the identification and interpretation of combustion features in prehistoric archaeological sites. *Journal of Archaeological Method and Theory*, **21**(3), 616–668.

Mentzer, S. M., and Quade, J., 2013. Compositional and isotopic analytical methods in archaeological micromorphology. *Geoarchaeology*, **28**(1), 87–97.

Mentzer, S. M., Romano, D. G., and Voyatzis, M. E., 2015. Micromorphological contributions to the study of ritual behavior at the ash altar to Zeus on Mt. Lykaion, Greece. *Archaeological and Anthropological Sciences*, doi:10.1007/s12520-014-0219-y.

Murray, A. S., and Mejdahl, V., 1999. Comparison of regenerative-dose single-aliquot and multiple-aliquot (SARA) protocols using heated quartz from archaeological sites. *Quaternary Science Reviews*, **18**(2), 223–229.

Namdar, D., Zukerman, A., Maeir, A. M., Katz, J. C., Cabanes, D., Trueman, C., Shahack-Gross, R., and Weiner, S., 2011. The 9th century BCE destruction layer at Tell es-Safi/Gath, Israel: integrating macro-and microarchaeology. *Journal of Archaeological Science*, **38**(12), 3471–3482.

Regev, L., Poduska, K. M., Addadi, L., Weiner, S., and Boaretto, E., 2010. Distinguishing between calcites formed by different mechanisms using infrared spectrometry: archaeological applications. *Journal of Archaeological Science*, **37**(12), 3022–3029.

Regev, L., Eckmeier, E., Mintz, E., Weiner, S., and Boaretto, E., 2011. Radiocarbon concentrations of wood ash calcite: potential for dating. *Radiocarbon*, **53**(1), 117–127.

Rhodes, E. J., Fanning, P. C., and Holdaway, S. J., 2010. Developments in optically stimulated luminescence age control for geoarchaeological sediments and hearths in western New South Wales, Australia. *Quaternary Geochronology*, **5**(2–3), 348–352.

Richter, D., 2007. Advantages and limitations of thermoluminescence dating of heated flint from Paleolithic sites. *Geoarchaeology*, **22**(6), 671–683.

Roebroeks, W., and Villa, P., 2011. On the earliest evidence for habitual use of fire in Europe. *Proceedings of the National Academy of Sciences*, **108**(13), 5209–5214.

Rogers, K. D., and Daniels, P., 2002. An X-ray diffraction study of the effects of heat treatment on bone mineral microstructure. *Biomaterials*, **23**(12), 2577–2585.

Rojo-Guerra, M. A., Garrido-Pena, R., and García-Martínez de Lagrán, I., 2010. Tombs for the dead, monuments to eternity: the deliberate destruction of megalithic graves by fire in the interior highlands of Iberia (Soria Province, Spain). *Oxford Journal of Archaeology*, **29**(3), 253–275.

Roos, C. I., 2008. *Fire, Climate, and Social-Ecological Systems in the Ancient Southwest: Alluvial Geoarchaeology and Applied Historical Ecology*. PhD dissertation. University of Arizona.

Rösch, M., Ehrmann, O., Herrmann, L., Schulz, E., Bogenrieder, A., Goldammer, J. P., Hall, M., Page, H., and Schier, W., 2002. An experimental approach to Neolithic shifting cultivation. *Vegetation History and Archaeobotany*, **11**(1–2), 143–154.

Sandgathe, D. M., Dibble, H. L., Goldberg, P., McPherron, S. P., Turq, A., Niven, L., and Hodgkins, J., 2011. Timing of the appearance of habitual fire use. *Proceedings of the National Academy of Sciences*, **108**(29), E298.

Schiegl, S., Goldberg, P., Bar-Yosef, O., and Weiner, S., 1996. Ash deposits in Hayonim and Kebara caves, Israel: macroscopic, microscopic and mineralogical observations, and their archaeological implications. *Journal of Archaeological Science*, **23**(5), 763–781.

Schiegl, S., Goldberg, P., Pfretzschner, H.-U., and Conard, N. J., 2003. Paleolithic burnt bone horizons from the Swabian Jura: distinguishing between *in situ* fireplaces and dumping areas. *Geoarchaeology*, **18**(5), 541–565.

Shahack-Gross, R., and Ayalon, A., 2013. Stable carbon and oxygen isotopic compositions of wood ash: an experimental study with archaeological implications. *Journal of Archaeological Science*, **40**(1), 570–578.

Shahack-Gross, R., Bar-Yosef, O., and Weiner, S., 1997. Black-coloured bones in Hayonim Cave, Israel: differentiating between burning and oxide staining. *Journal of Archaeological Science*, **24**(5), 439–446.

Shahack-Gross, R., Berna, F., Karkanas, P., Lemorini, C., Gopher, A., and Barkai, R., 2014. Evidence for the repeated use of a central hearth at Middle Pleistocene (300 ky ago) Qesem Cave, Israel. *Journal of Archaeological Science*, **44**, 12–21.

Shahack-Gross, R., Ayalon, A., Goldberg, P., Goren, Y., Ofek, B., Rabinovich, R., and Hovers, E., 2008. Formation processes of cemented features in karstic cave sites revealed using stable oxygen and carbon isotopic analyses: a case study at Middle Paleolithic Amud Cave, Israel. *Geoarchaeology*, **23**(1), 43–62.

Shoval, S., Erez, Z., Kirsh, Y., Deutsch, Y., Kochavi, M., and Yadin, E., 1989. Determination of the intensity of an early Iron Age conflagration at Tel-Hadar, Israel. *Thermochimica Acta*, **148**, 485–492.

Stahlschmidt, M. C., Miller, C. E., Ligouis, B., Hambach, U., Goldberg, P., Berna, B., Richter, D., Urban, B., Serangeli, J., and Conard, N. J., 2015. On the evidence for fire at Schöningen. *Journal of Human Evolution*, Special Issue Schöningen, **89**.

Théry-Parisot, I., 2002. Fuel management (bone and wood) during the Lower Aurignacian in the Pataud rock shelter (Lower Palaeolithic, Les Eyzies de Tayac, Dordogne, France). Contribution of experimentation. *Journal of Archaeological Science*, **29**(12), 1415–1421.

Thompson, T. J. U., Islam, M., and Bonniere, M., 2013. A new statistical approach for determining the crystallinity of heat-altered bone mineral from FTIR spectra. *Journal of Archaeological Science*, **40**(1), 416–422.

Toffolo, M. B., Maeir, A. M., Chadwick, J. R., and Boaretto, E., 2012. Characterization of contexts for radiocarbon dating: results from the early Iron Age at Tell es-Safi/Gath, Israel. *Radiocarbon*, **54**(3–4), 371–390.

Van Keuren, S., and Roos, C. I., 2013. The geomorphology of Kiva Closure at Fourmile Ruin, Arizona. *Journal of Archaeological Science*, **40**(1), 615–625.

Verhoeven, M., 2000. Death, fire and abandonment. *Archaeological Dialogues*, **7**(1), 46–65.

Villagran, X. S., 2014. Experimental micromorphology on burnt shells of *Anomalocardia brasiliana* (Gmelin 1791) (Bivalvia, Veneridae) and its potential for identification of combustion features on shell-matrix sites. *Geoarchaeology*, **29**(5), 389–396.

Wadley, L., Sievers, C., Bamford, M., Goldberg, P., Berna, F., and Miller, C., 2011. Middle Stone Age bedding construction and settlement patterns at Sibudu, South Africa. *Science*, **334**(6061), 1388–1391.

Wilson, C. A., Davidson, D. A., and Cresser, M. S., 2008. Multi-element soil analysis: an assessment of its potential as an aid to archaeological interpretation. *Journal of Archaeological Science*, **35**(2), 412–424.

Wrangham, R. W., Jones, J. H., Laden, G., Pilbeam, D., and Conklin-Brittain, N., 1999. The raw and the stolen: cooking and the ecology of human origins. *Current Anthropology*, **40**(5), 567–594.

Cross-references

Analysis of Carbon, Nitrogen, pH, Phosphorus, and Carbonates as Tools in Geoarchaeological Research
Archaeomagnetic Dating
Burned-Rock Features
Dust Cave, Alabama
Electron Spin Resonance (ESR) in Archaeological Context
Field Geochemistry
Fourier Transform Infrared Spectroscopy (FTIR)
Gesher Benot Ya'aqov
Hohle Fels
Kebara Cave
Living Surfaces
Luminescence Dating of Pottery and Bricks
Magnetometry for Archaeology
Optically Stimulated Luminescence (OSL) Dating
Paleomagnetism
Pastoral Sites
Radiocarbon Dating
Soil Micromorphology
Stable Carbon Isotopes in Soils
Sterkfontein/Swartkrans/Kromdraai
Susceptibility
Trampling
Zhoukoudian

HOHLE FELS

Christopher E. Miller
Geoarchaeology, Institute for Archaeological Sciences, Senckenberg Centre for Human Evolution and Paleoenvironment, University of Tübingen, Tübingen, Germany

Hohle Fels is a Paleolithic cave site located in the Swabian Jura region of southwestern Germany. It is well known for containing a cultural sequence spanning the Middle to Upper Paleolithic transition and for its evidence of Aurignacian portable art and musical instruments.

Hohle Fels, together with other well-known sites such as Geißenklösterle, Sirgenstein, and Brillenhöhle, is located in the Ach Valley, a tributary of the Danube River. The steeply sided valley was carved out by the Danube before avulsing into its modern drainage prior to the Riss glaciation. Hohle Fels and the other cave sites in the valley are remnant phreatic tubes formed within the Jurassic limestone of the region.

Bear teeth and reindeer bones were first collected in the cave in the 1830s, and the site was extensively excavated for its guano deposits in the 1840s. O. Fraas and T. Hartmann conducted the first scientific excavations at Hohle Fels in 1870–1871. R. R. Schmidt excavated there in 1906, and G. Riek and G. Matschak excavated in the cave between 1958 and 1960. During fieldwork at Geißenklösterle, J. Hahn conducted limited excavations at the site (1977–1979), returning in 1988 for more extensive investigations. Excavations at Hohle Fels are ongoing under the direction of N. J. Conard.

The site contains a cultural sequence spanning the Middle Paleolithic, Aurignacian, Gravettian, and Magdalenian. The Aurignacian at Hohle Fels, along with nearby Geißenklösterle, is famous for its figurative art, carved out of mammoth ivory and depicting a wide variety of animals (Conard, 2003). The site also contains one of the earliest representations of the human female form: the so-called Venus of Hohle Fels (Conard, 2009). In addition to figurative art, Hohle Fels and Geißenklösterle contain the remains of several bird-bone flutes.

Depositional processes at the site are complex and have been the subject of micromorphological study (Goldberg et al., 2003). The cave has a front entrance and a chimney in the back, both of which served as entry points for sediment. Loess, which accumulated on the plateau backing the cave, was washed into the chimney, forming a large sediment cone in the rear of the cave. Here, the calcareous loess was phosphatized in the presence of bat guano. The material moved downslope through colluvial processes and mixed with fresh loess which entered the cave through the front entrance. Following final deposition, the sediments were influenced by freeze-thaw processes, forming lenticular microstructures and rounded, cryoturbated coated aggregates.

Humans acted as significant depositional agents during the Upper Paleolithic occupations of Hohle Fels, as evidenced by the preservation of extensive combustion features. Notably, layer 3cf, dating to the Gravettian, extended across the entire area of excavation and was 5–15 cm thick. It was largely composed of sand-sized fragments of burnt and unburnt bone. Micromorphological analysis of this layer suggested that it formed when people, who were using bone as a fuel, cleaned their hearths and dumped the remains within the cave (Schiegl et al., 2003).

Bibliography

Conard, N. J., 2003. Palaeolithic ivory sculptures from southwestern Germany and the origins of figurative art. *Nature*, **426**(6968), 830–832.

Conard, N. J., 2009. A female figurine from the basal Aurignacian of Hohle Fels Cave in southwestern Germany. *Nature*, **459**(7244), 248–252.

Goldberg, P., Schiegl, S., Meligne, K., Dayton, C., and Conard, N. J., 2003. Micromorphology and site formation at Hohle Fels Cave, Swabian Jura, Germany. *Eiszeitalter und Gegenwart*, **53**(1), 1–25.

Schiegl, S., Goldberg, P., Pfretzschner, H.-U., and Conard, N. J., 2003. Paleolithic burnt bone horizons from the Swabian Jura: distinguishing between in situ fireplaces and dumping areas. *Geoarchaeology*, **18**(5), 541–565.

HOUSE PITS AND GRUBENHÄUSER

Richard I. Macphail
Institute of Archaeology, University College London, London, UK

Synonyms

Grophus (Swedish); Grubenhaus; Grubenhäuser (plural German); Le Cabane en Fosse (Swiss-French); Le fond de cabane (French); Pit house; Sunken feature building ("SFB"; UK term for undifferentiated pit house structures) (West, 1985, 14).

Definition

House pits (pit houses) and grubenhäuser are sunken feature buildings (SFB) where activities took place either (1) in the pit itself (in theory forming occupation floor deposits in the house pit) or (2) on an overlying planked surface laid atop the pit, which then functioned as an air space, or crawl space, in which case the archaeological remains would be mainly characterized as postdepositional fills (Tipper, 2004).

Introduction

House pits and grubenhäuser occur in a number of ancient cultures worldwide, but they were constructed and functioned differently within each culture. Some pit houses are clearly pit houses sensu stricto, with the base of the pit house acting as a floor surface, including a ramp or step-down (e.g., West Coast Native American, First Nation Canadians, and late prehistoric groups of Southwestern United States and northwestern Mexico, Jomon Period Japan, and Bronze Age Korea). In contrast, mainly during the Migration Period in Europe (~AD 400–800), the pit part of the structure was simply a wooden-supported, planked-over air space, and activities took place on this wooden floor (Gustavs, 1998; Tipper, 2004, 160 ff.). This is typical of France, Germany, England, and Scania (South Sweden), for example, although in Bulgaria, Poland, and Ukraine, "Slav" pit houses included a hearth in one corner and functioned as a pit house sensu stricto; some Swedish examples may also date to the Early Bronze Age (Kobylínski, 1989; Tesch, 1992; Tipper, 2004, 3; Henning, 2011, "personal communication"). Some twenty SFBs of Roman age (second century AD) are about 9 × 4.8 m in size and cut into chalk at Monkton, Isle of Thanet, Kent, UK, but though they can have stepped entrances, there were no occupation floor deposits; it is believed that a plank floor had been laid on the rammed chalk "floor" (Bennett, 1997). The exact origin of these structure types remains enigmatic, and they are so far unique in the UK. A further complication is that while pit houses in early and middle Saxon England functioned with an air space, Late Saxon (~AD 800–1050) pit houses could have a below-floor cellar and are therefore called cellared buildings. This is why the UK generic term "SFB" is often employed for such structures. Specialized subterranean features such as the "Kiva" of the Southwestern United States, crypts, and Mithraic temples of Roman Europe (e.g., Rentzel, 2011) may also have some aspects in common with pit house use and hypothetical trampled floor development.

In the Southwestern United States and northwestern Mexico, three types of habitations with some subterranean component were important constructions of the Early Agricultural period (AD 200–900) (Cordell and McBrinn, 2012, 158–161): (1) simple circular or oval structures built over shallow depressions, (2) houses-in-pits (where the pit floor extended out past the walls of the structure), and (3) true pit houses (where the walls of the structure incorporated the sites of the pit). The distinction between the latter two forms may be important because "domestic architecture is a conservative and functional technology, and the method of construction may be indicative of socialization and identity" (Herr and Young, 2012, 8). Little in the way of specific geoarchaeological data is available for these otherwise well-known structures of the North American archaeological record.

Sediment studies have been carried out mainly on pit houses in North America and on grubenhäuser across Europe (Simpson et al., 1999; Goldberg, 2000; Macphail et al., 2006). Some naturally formed subsoil features may contain artifacts but are not necessarily constructed dwellings sites (Newell, 1980), and thin sections have been employed to differentiate tree-throw subsoil hollows and pit features in general from pit houses sensu stricto (Macphail et al., 2008).

Occupation floor deposits and weathering in subterranean structures

In theory, the basal deposits of pit houses should record occupation activities and human traffic. As analogues, well-preserved microlaminated occupation floor deposits have been found that recorded floor constructions and supposed human traffic. One example is at a crypt in Guildford, UK, where heavy trampling bought in large amounts of fine-burned hearth and kitchen waste debris over a series of chalk floors (Figure 1). A second example is at the Biesheim Mithraeum, Alsace, France; here, only small traces of trampled-in anthropogenic material were recorded between mortar floor renewal layers, possibly because of the highly ritualized nature of the occupation (Rentzel, 2011). In Southwestern United States, mineralogical study of pit house floors using backscatter electron microscopy yielded evidence of increased weathering of

House Pits and Grubenhäuser, Figure 1 Guildford, UK; scan of thin section of medieval church crypt floor constructed of rammed chalk containing frequent coarse sand and fine gravel. Note layered beaten floor accumulation bringing in burned kitchen waste, rich in wood charcoal and burned bone, indicative of in situ trampling. Frame width is ~65 mm.

the house floor compared to the land surface around the habitation (Pope and Rubenstein, 1999). This was taken as evidence that more focused human habitation produced more intense weathering. It always has to be remembered, however, that any form of subsoil hollow will be more influenced by drainage effects compared to the surrounding soils (Veneman et al., 1984).

Hunter and gatherer house pit sites

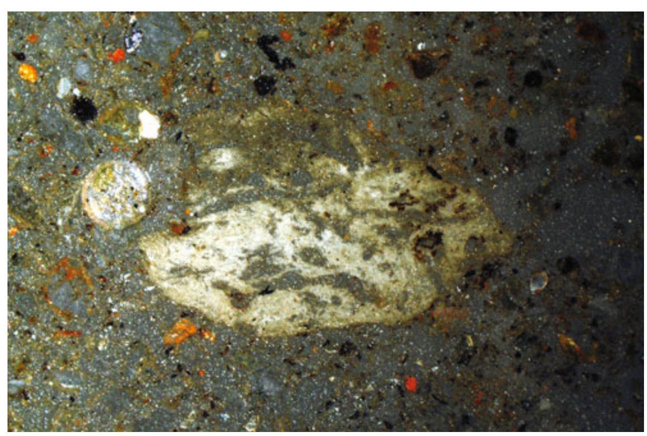
In contrast to these subterranean examples, pit house occupation deposits are less commonly well preserved because of a series of postdepositional processes active in earth and wood-based constructions. The hunters and gatherers of the First Nation Canadians settlement site at Keatley Creek (British Columbia, Canada), for example, has been under investigation since 1996 (e.g., Goldberg, 2000; Hayden, 2004; Villeneuve, 2009, "personal communication"). The first major house pits appear to have been constructed beginning at about 4800 BP, but the major period of occupation was during the Plateau (2400–1200 BP) and the early Kamloops (1200–1000 BP) horizons. The largest pit houses are 18–21 m in diameter (Figure 2), and pit houses have apparently homogeneous soil fills. Soil micromorphology studies by Goldberg (2000, and unpublished reports) and Macphail (unpublished reports) found that several processes often make it difficult to reconstruct these sites:

- Scavenging and digging (coprolitic traces) of canids and other essentially carnivorous animals (Figure 3)
- Structural collapse (pit sides and roof infills)
- Burrowing by insects (e.g., cicadas)
- Tree rooting and acid soil leaching

Floor layers have often been mixed, and ashes have commonly been dissolved by soil acidity. Nevertheless, studies of pit house floor layers, pit house rim deposits, pit fills, and plaza areas have yielded burned bone (including calcined bone), fish bone, charcoal evidence of hearths and kitchen waste, and phytolith concentrations representing possible grass roof or matting material. One exceptional floor sample was examined in 2009 (Goldberg, unpublished report). It comprised three floor sequences, where each sequence commenced at its base with a layer of moderately sorted silty sand (e.g., 1 and 2) or sand (e.g., 3), overlain by a finer layer of silty clay, commonly with remains of reddish brown organic material (matting?), and lastly, a layer of calcareous plaster (micrite, or microcrystalline calcite).

Finally, it can be noted that even the study of a Neolithic (2000–2500 BC) sunken long house site at Bjästamon, Ångermanland, North Central Sweden, employing ten thin sections, failed to identify intact floors, again because of intensive postdepositional bioworking under boreal coniferous woodland, with acid leaching and weak podzolization also occurring. Instead, the remains of Neolithic combustion zone (hearths) and midden waste occur as several concentrations of rare coarse (maximum 2.5 mm) and many fine charcoal fragments, burned mineral grains, rare coprolitic?/scat remains composed of very fine leached bone (upwards of 17 fragments, maximum 1.2 mm), and rare burned bone. These occur alongside trace amounts of possible burned shell (1–4 fragments up to 680 μm); this site would have been on the coast 4,000–4,500 years ago – it was affected by postglacial uplift. One coprolitic fragment included cereal material. These are useful traces that testify to the presence of kitchen waste and probably

House Pits and Grubenhäuser, Figure 2 Keatley Creek, British Columbia, Canada; field photo of First Nation Canadian multiperiod (~4800–1200 BP) pit house settlement; "footprint" of large pit house in foreground (Paul Goldberg as scale); numerous other pit houses can be seen in the background.



House Pits and Grubenhäuser, Figure 3 Keatley Creek, British Columbia, Canada; photomicrograph of thin section 07-2a, typically loose and bioworked pit house fill, here with whitish (canid?) coprolite fragments, and scattered fine charcoal. Fills were typically scavenged and dug up, then worked by mesofauna, intermediate soil organisms that feed on microorganisms and decaying materials. Oblique incident light (*OIL*), frame width is 2.38 mm.

the penecontemporaneous working of the deposits by scavenging canids (?), a situation clearly resembling that of Canadian pit houses. Another Swedish example is a late Mesolithic-Early Neolithic pit house at Vuollerim, Norrbotten, North Sweden, which has phosphate concentrations associated with bone debris concentrations (Linderholm, 2010).

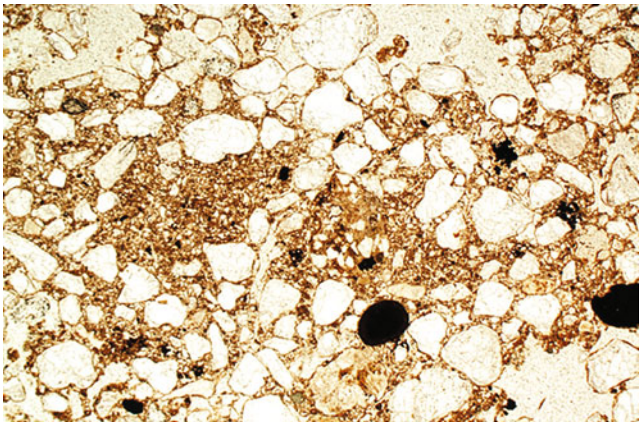
Grubenhäuser

Reviews and fieldwork show that when excavated, grubenhäuser can reveal subrectangular pits 4–6 m in length with depths of between 0.30 and 1.00 m. They may or may not have post holes, with some having 2 post holes, others 4–6 (Tipper, 2001, 2004; Macphail et al., 2006; Thomas, 2010) (see Figure 7). Sometimes, loom weights are found within their fills (see below), and this had led to the view that the grubenhäuser were weaving sheds. Their small size, however, generally makes this common interpretation debatable, except of course for the very long and large grubenhaus at the palace of Tilleda, Saxony-Anhalt, Germany, which is clearly reconstructed as a "weaving shed" (Grimm, 1968). Tipper (2004, 33ff.) reviewed grubenhäuser from Europe, including the major Anglo-Saxon sites of England in Mucking, Essex, West Stow, Suffolk, and West Heslerton, North Yorkshire, where 53, 69, and 90 grubenhäuser, respectively, have been excavated. In broad terms, these have either bipartite or tripartite fills (i.e., 2–3 layers), but none of these seemed to contain records suggesting use of the pit itself; they were deemed dominantly (post-abandonment) tertiary fills, rather than use or constructional fills. It should be noted that when settlements are excavated, these SFBs occur alongside larger and longer post-built halls, clearly indicating that pit houses were not the main dwelling structure.

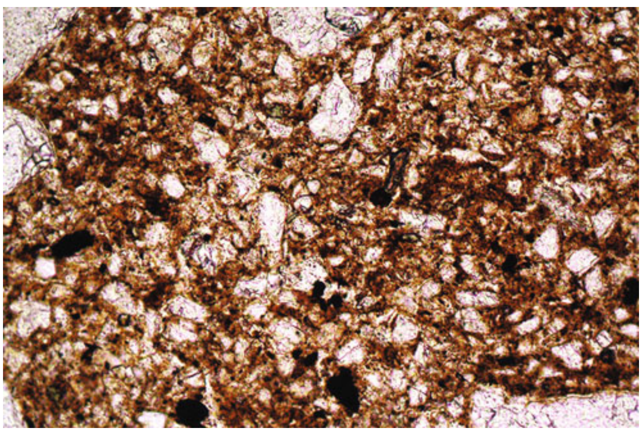
Fills can, however, include constructional residues, including extremely rare remains of planking – wood stains at Dahme-Spreewald, Germany (Gustavs, 1998); ferruginized wood at Lyminge, Kent (Macphail, 2011); burned planks from a suspended plank floor in SFB 15 at West Stow (West, 1985); and more commonly, turf fragments (possibly from load-bearing low walls). Chalky cob and chalky mortar have also been observed. Turf fragments provide useful proxy information on the local environment. In addition, ash and charcoal were found in the pit of a modern grubenhaus, built then razed at the reconstructed Anglo-Saxon village of West Stow, Suffolk, UK; this mixed burned debris occurs over the lowermost fill, which is composed of soil that had fallen down between the planks of the suspended plank floor (French and Milek, 2012).

Trampled pit "floor" deposits have never been observed in the very numerous UK grubenhäuser that have been studied. On the other hand, some lowermost fills may contain clues to function, and the presence of phytoliths and small amounts of cereal material have suggested a plausible grain store use. A storage function is the most favored interpretation by Tipper (2004, 185) because of the pit air space and benefits of airflow through a suspended plank floor. Most fills have been homogenized by biological activity attracted to the fills, but one Cambridgeshire example (Durnford Farm, Sawston, UK) had intact laminated use fills (Macphail and Crowther, 2011) (Figures 4, 5, and 6). This material, which presumably "silted" down through the spaces between the planks (see West Stow above), is composed of moderately poorly preserved alternating sands and silts, the latter particularly including humified fine organic matter and some fine charcoal. These laminae, however, simply record tracking-in of local decalcified topsoil, from a landscape probably managed by fire (perhaps pasture), with this grubenhaus likely being constructed at a "greenfield" site or at the edge of a settlement. Another rare case of preserved plank floor deposits was found at Lyminge, Kent (Thomas, 2010) (Figures 7, 8, and 9). Here, an AD 580/600–640/660 grubenhaus (SFB 1) was found with a 6 kg iron plow coulter at the bottom of the fill. This grubenhaus was 4.70 m by 3.60 m and 0.50 m deep, and it is present alongside 2 others in addition to a 12.8 × 4.6 m post-built hall. In SFB 1, iron salts from the coulter apparently ferruginized plank floor remains and sealed small amounts of occupation soil between it and the chalk substrate into which the grubenhaus pit had been cut. One 30 mm thick example showed that the chalky soil fill includes fine charcoal, an example of coprolitic waste, and amorphous organic

House Pits and Grubenhäuser, Figure 4 Sawston (Durnford Farm), Cambridgeshire, UK; field photo of Middle Saxon (~600–800 AD; SFB 2047) grubenhaus fill; sampling of primary fills from the balk, including rare discontinuous use secondary fills from occupation soil apparently falling through putative plank floor (*arrows*; fruit juice carton sample, Context 2049) (see Figures 5 and 6), and above that more obvious dark tertiary fill (sampled with Kubiena box M2, Context 2048) albeit with only 1.19 % LOI (loss on ignition), 1.55 mg g^{-1} P, and 2.35 % $\chi_{conv.}$, recording small amounts of anthropogenic inputs (burned mineral material, charcoal, ash, coprolitic material, etc.).



House Pits and Grubenhäuser, Figure 5 Sawston, Cambridgeshire, UK; photomicrograph of Context 2049, showing laminated sands and humic silts, of hypothetical plank floor silting origin, and recording actual use of the grubenhaus rather than tertiary infilling. Plane polarized light, frame width is ~4.62 mm.

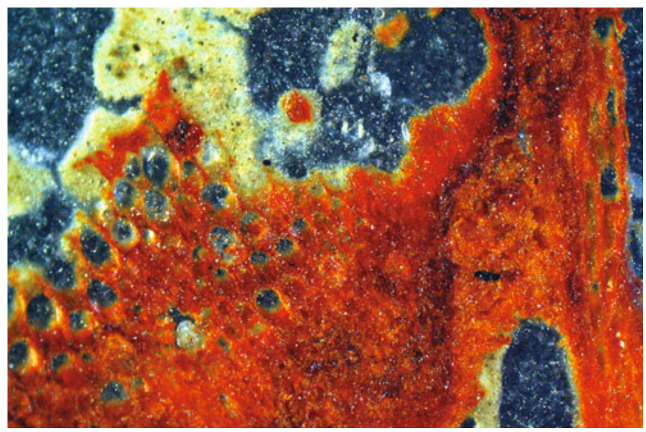


House Pits and Grubenhäuser, Figure 6 Sawston, Cambridgeshire, UK; photomicrograph of Context 2049, detail of humic silts, which include amorphous organic matter of possible dung origin (max 1.19 mg g^{-1} P); these silts suggest occupation of a rural soil environment that included animal management. Plane polarized light, frame width is ~0.90 mm.

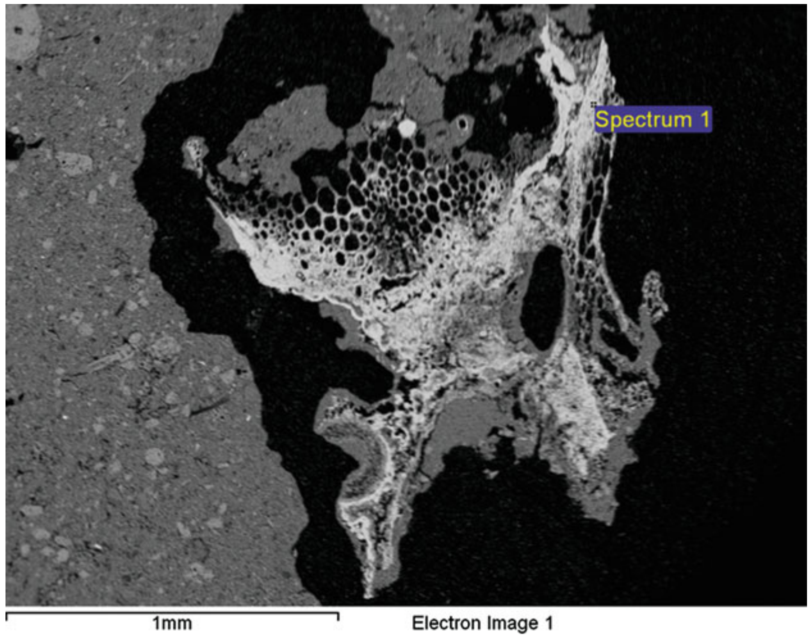
matter, which with the presence of fungal material may perhaps suggest a dung origin. This may record occupation silting through gaps in the putative plank floor. Probable earthworm burrows seem to include the "fossilized" remains of ferruginized and phosphate-enriched organic matter, again perhaps of dung origin – dung having been worked by these invertebrates. Like many SFBs, a rural settlement including animal management is not unexpected (after disuse or abandonment, chalky soil washed into this occupation fill.)

In fact, the fills of grubenhäuser often reflect the local environment of the settlement in which they were situated. For example, soil fragments from the cut of the pit provide soil data. It has been found in England and Scania (Sweden), for example, that fills occur as either of two contrasting types. These are essentially (1) archaeologically sterile fills reflecting the local (original) "greenfield" environment, with no relative phosphate enrichment and magnetic susceptibility

House Pits and Grubenhäuser, Figure 7 Lyminge, Kent, UK; field photo of typical Saxon grubenhaus (~560–660 AD; SFB 1), showing a pair of primary posts located on a longitudinal axis of the pit, both of which had been replaced during the lifetime of the structure, together with an additional six posts located at the corners and the midpoint of each of the longitudinal sides of the pit (photo courtesy of G. Thomas, University of Reading, UK). The iron plow coulter was found in a basal fill of the pit, some 30 mm above the chalk substrate exposed in the photo.



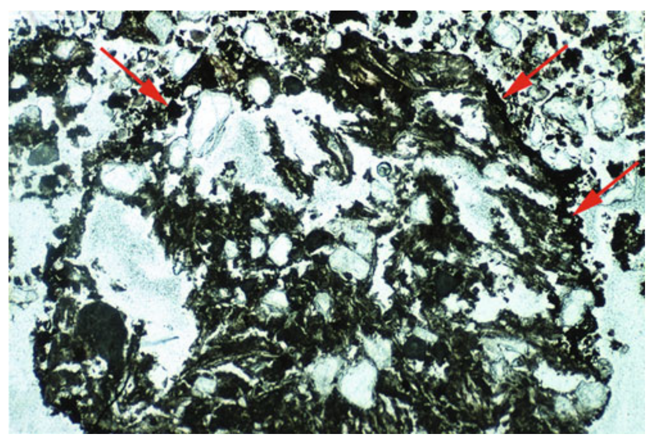
House Pits and Grubenhäuser, Figure 8 Lyminge, Kent, UK; photomicrograph of 1 mm thick iron pan formed under the iron plow coulter found in SFB 1. Here iron salts have pseudomorphically preserved wood comprising cells showing two lines of orientation, interpreted as knotwood that was relatively resistant to decay (see Figure 9). This is probably relict of a putative plank floor upon which the coulter was placed. Oblique incident light (OIL), frame width is ~0.90 mm.



House Pits and Grubenhäuser, Figure 9 Lyminge, Kent, UK; EDS (energy dispersive spectrometry) X-ray backscatter image of knotwood showing bright reflectance of iron impregnation (mean 65.6 % Fe). Mean 2.40 % P indicates that phosphate in the pit has also been concentrated into this iron pan-preserved wood. Spectrum 1 measured an example of this FeP concentration. Scale is 1 mm.

(MS) enhancement, or (2) fills that are strongly anthropogenic in character with clear phosphate enrichment and MS enhancement (data from 22 grubenhäuser; Macphail et al., 2006). The latter is a typical tertiary fill with dog and human coprolites, cess staining, and weakly to strongly burned microartifacts (e.g., bone, daub). It indicates local middening and accumulation of settlement waste ("cultural soils"). Dumped cess was also recorded in the Swiss Jura (Guélat and Federici-Schenardi, 1999), while in poorly draining sites, vivianite originating from secondary phosphate concentration occurs (Tempsford, Bedfordshire, UK). Unfired "clay" loom weights (e.g., composed of local silty clays on sandy soil sites) are often found, because they are preferentially preserved in these pit house fills. Dung residues also occur, e.g., probably from cattle in Scania and southern England and from sheep at West Heslerton (on edge of North Yorkshire Wolds; Figure 10); along with cereal processing waste, they testify to mixed farming activity.

Grubenhäuser can also include Late Saxon cellared buildings in England. One AD 875–1000 example at Whitefriars, Canterbury, UK, has an in situ pit floor lining/mud-plastered brick earth floor (brick earth = a Pleistocene loess-rich alluvium that was commonly employed to make bricks from Tudor times onwards). This has been subsequently partially mixed with much fine charcoal, rubefied mineral grains, and phytoliths,



House Pits and Grubenhäuser, Figure 10 West Heslerton, North Yorkshire, Yorkshire (chalk) Wolds, UK; Middle Saxon (~600–800 AD) grubenhaus fill (sample 140); secondary fill includes partially ashed ovi-caprid dung pellet associated with major sheep husbandry recorded at the settlement. Burned debris recording final fills of the grubenhäuser at West Heslerton includes "red ash," here as opaque material coating the burned dung pellet (*arrows*). Microprobe found: ashed dung pellet (e.g., 31.9 % Ca, 0.43 % Fe, 0.19 % P, 0.12 % S, 0.24 % K, 0.23 % Mn); anomalously iron-rich "red ash" (e.g., 0.62 % Ca, 11.7 % Fe, 0.23 % P, 0.04 % S, 0.0 % K, 0.84 % Mn); chalk (e.g., 27.5–38.7 % Ca). Plane polarized light, frame width is ~5.5 mm.

including articulated phytoliths. The site has been interpreted as the razed remains of a cereal processing/cereal storehouse (Macphail and Crowther, 2007). No trampled pit house floor was recognized, however. In contrast, the pit house fill of a ninth century AD cellared SFB at Place Street, Norwich, UK, recorded a 2 cm thick phosphate-enriched beaten floor over basal leveling deposits, testifying to use of this cellar (Macphail and Crowther, 2009). The structure burned down, and debris in the fill included chalk lime-rendered burned planks. In addition, burned thatch residues of siliceous slag also occur. These ashed and charred straw remains include vesicles relict of natural plant pores within the straw. Another example of structures with subsoil pit features is the Belgium Roman to medieval "postal" (Flemish/Dutch). For example, at Brecht Zoegweg in Belgium, locally collected turves were used to line the sunken animal byre, and they became enriched in urine and excrements of the stabled animals kept overnight or over winter (Mikkelsen et al., 2003). This fill material is then employed to manure fields, creating plaggen soils.

Summary

Pit house and grubenhäuser structures are described from the New and Old World. Pit house fills from Canada and Sweden were generally found to be very strongly worked by scavenging animals, soil mesofauna, and plant roots, while anthropogenic materials are highly dispersed. No intact pit floor trampled deposits were identified because of this postdepositional working; special sub-ground structures such as a Mithraic temple, however, had recorded floor trampling. Most European grubenhäuser of the Migration Period apparently had a suspended plank floor over the pit (apart from Slav pit houses). Most pit fills are of tertiary origin. Rare examples of sediments resulting from grubenhäuser use are provided.

Bibliography

Bennett, P., 1997. Monkton. *Current Archaeology*, **151**, 258–264.

Cordell, L. S., and McBrinn, M. E., 2012. *Archaeology of the Southwest*, 3rd edn. Walnut Creek: Left Coast Press.

French, C., and Milek, K., 2012. The Geoarchaeological evidence. In Tipper. J. (ed.), *Experimental Archaeology and Fire: the investigation of a burnt reconstruction at West Stow Anglo-Saxon village*. East Anglian Archaeology 146. Bury St Edmunds: Archaeological Service, Suffolk County Council, pp. 77–89.

Goldberg, P., 2000. Micromorphological aspects of site formation at Keatley Creek. In Hayden, B. (ed.), *The Ancient Past of Keatley Creek*. Burnaby: Simon Fraser University, Archaeology Press, pp. 79–95.

Grimm, P., 1968. *Tilleda. Eine Königspfalz am Kyffhäuser*. Teil 1: Die Hauptburg. Berlin: Deutsche Akademie der Wissenschaften zu Berlin, Schriften der Sektion Ur- und Frühgeschichte.

Guélat, M., and Federici-Schenardi, M., 1999. Develier-Courtételle (Jura): L'histoire d'une cabane en fosse reconstituée grâce à la micromorphologie. *Helvetica Archaeologica*, **118–119**, 58–63.

Gustavs, S., 1998. Spätkaiserzeitliche Baubefunde von Klein Köris, Lkr. Dahme-Spreewald. In Henning, J., and Leube, A. (eds.), *Haus und Hof im östlichen Germanien: Tagung, Berlin vom 4. bis 8. Oktober 1994*. Bonn: Habelt. Universtätsforschungen zur prähistorischen Archäologie Band 50, and Schriften zur Archäologie der germanischen und slawischen Frühgeschichte Band 2, pp. 40–66.

Hayden, B., 2004. *The Ancient Past of Keatley Creek. Volume III: Excavations and Artifacts*. Burnaby: Archaeology Press, Simon Fraser University.

Herr, S. A., and Young, L. C., 2012. Introduction to Southwest pithouse communities. In Young, L. C., and Herr, S. A. (eds.), *Southwestern Pithouse Communities, AD 200–900*. Tucson: University of Arizona Press, pp. 1–13.

Kobylínski, Z., 1989. An ethnic change or a socio-economic one? The 5th and 6th centuries AD in the Polish lands. In Shennan, S. (ed), *Archaeological Approaches to Cultural Identity*. One World Archaeology 10. London: Unwin Hyman, pp. 303–310.

Linderholm, J., 2010. Soil prospection: chemical and magnetic susceptibility attributes from off-site and intra-site perspectives. A case study from a late Mesolithic-early Neolithic dwelling in northern Sweden. In Linderholm, J. (ed.), *The Soil as a Source Material in Archaeology. Theoretical Considerations and Pragmatic Applications*. Archaeology and Environment 25. Umeå: Umeå University, pp. 1–43.

Macphail, R. I., 2011. *Lyminge Early Saxon Plough Coulter-Associated Soil, Lyminge, Kent (LYM10): Soil Micromorphology Including SEM/EDS*. Unpublished report to Reading University. London: Institute of Archaeology, University College London.

Macphail, R. I., and Crowther, J., 2007. *Whitefriars, Canterbury: Soil Micromorphology, Chemistry and Magnetic Susceptibility*. Unpublished report for Canterbury Archaeological Trust. London: Institute of Archaeology, University College London.

Macphail, R. I., and Crowther, J., 2009. *Busseys, Place Street, Norwich (26442N): Soil Micromorphology, Chemistry and Magnetic Susceptibility of Monolith Sample 15 from Structure A*. Unpublished report for Norfolk Archaeological Unit. London: Institute of Archaeology, University College London.

Macphail, R. I., and Crowther, J., 2011. *SFB 2047, Durnford Farm, Sawston, Cambridgeshire: Soil Micromorphology, Chemistry and Magnetic Susceptibility*. Unpublished report for Archaeological Solutions. London: Institute of Archaeology, University College London.

Macphail, R. I., Linderholm, J., and Karlsson, N., 2006. Scanian pithouses; interpreting fills of grubenhäuser: examples from England and Sweden. In Engelmark, R., and Linderholm, J. (eds.), *Proceedings from the 8th Nordic Conference on the Application of Scientific Methods in Archaeology in Ümea 2001*. Umeå: Umeå University. Archaeology and Environment 21, pp. 119–127.

Macphail, R. I., Haită, C., Bailey, D. W., Andreescu, R., and Mirea, P., 2008. The soil micromorphology of enigmatic early neolithic pit-features at Măgura, southern Romania. *Asociația Română de Arheologie, Studii de Preistorie*, **5**, 61–77.

Mikkelsen, J. H., Langohr, R., Macphail, R. I., and Vanwesenbeeck, V., 2003. Roman postal byres, a case study from the covers and belt of northern Belgium. In Boschian, G. (ed.), *Second International Conference on Soils and Archaeology, Pisa, 12th–15th May, 2003. Extended Abstracts*. Pisa: Dipartimento di Scienze Archeologiche, Università di Pisa, pp. 118–119.

Newell, R. R., 1980. Mesolithic dwelling structures: fact and fantasy. In Gramsch, B. (ed.), *Mesolithikum in Europa; 2. Internationales Symposium, Potsdam, 3. bis 8. April 1978: Bericht*. Veröffentlichungen des Museums für Ur- und Frühgeschichte Potsdam, Band 14–15. Berlin: Deutscher Verlag der Wissenschaften, pp, 235–284.

Pope, G. A., and Rubenstein, R., 1999. Anthroweathering: theoretical framework and case study for human-impacted weathering. *Geoarchaeology*, **14**(3), 247–264.

Rentzel, P., 2011. Spuren der nutzung in Mithraeum von Biesheim. Mikromorphologische Untersuchungen [Traces of the use of the Biesheim Mithraeum. Micromorphological investigations], annexed to Fortuné, C., Le mithraeum, une fouille ancienne revisiteé. In Reddé, M. (ed.), *Oedenburg: fouilles françaises, allemandes et suisses à Biesheim et Kunheim, Haut-Rhin, France*, Vol. 2. L' agglomération civile et les sanctuaries, Pt 2. Matérial et etudes. Mainz: Verlag des Römisch-Germanischen Zentralmuseums, pp. 250–257, 294.

Simpson, I. A., Milek, K. B., and Guðmundsson, G., 1999. A reinterpretation of the great pit at Hofstaðir, Iceland using sediment thin-section micromorphology. *Geoarchaeology*, **14**(6), 511–530.

Tesch, S., 1992. House, farm and village in the Köpinge area from the early Neolithic to the Early Middle Ages. In Larsson, L., Callmer, J., and Stjernquist, B. (eds.), *The Archaeology of the Cultural Landscape. Fieldwork and Research in a South Swedish Rural Region*. Acta Archaeologica Ludensia, Series in 4°, no. 19. Stockholm: Almqvist and Wiksell, pp. 283–344.

Thomas, G., 2010. 'Life before the Anglo-Saxon Minster': interim report on University of Reading Excavations at Lyminge. http://www.reading.ac.uk/archaeology/research/Lyminge/arch-lyminge2010.aspx. Reading: University of Reading.

Tipper, J., 2001. *Grubenhäuser: Pit Fills and Pitfalls*. PhD dissertation from Cambridge University.

Tipper, J., 2004. *The Grubenhaus in Anglo-Saxon England: An Analysis and Interpretation of the Evidence from a Most Distinctive Building Type*. Yedingham: Landscape Research Centre.

Veneman, P. L. M., Jacke, P. V., and Bodine, S. M., 1984. Soil formation as affected by pit and mound microrelief in Massachusetts, USA. *Geoderma*, **33**(2), 89–99.

West, S. E., 1985. *West Stow, Suffolk: The Anglo-Saxon Village*, 2 vols. East Anglian Archaeology 24. Suffolk: County Planning Department.

Cross-references

Experimental Geoarchaeology

I

INDUCTIVELY COUPLED PLASMA-MASS SPECTROMETRY (ICP-MS)

Hector Neff
Department of Anthropology and IIRMES, California State University Long Beach, Long Beach, CA, USA

Synonyms

Inductively coupled plasma mass spectrometry

Definition

A technique used for characterizing archaeological artifacts and sediments in terms of both elemental concentrations and isotope ratios.

Introduction

ICP-MS stands for inductively coupled plasma mass spectrometry. It is an analytical-chemistry technique that can measure even tiny (subpart per million) concentrations of most elements of the periodic table. In archaeology and geoarchaeology, elemental characterization by ICP-MS or other techniques is most commonly used for determining the sources of artifact raw materials. Other applications of elemental characterization include reconstructing technology and identifying and mapping activity areas on occupation floors. Some ICP-MS instruments can determine isotopic ratios with sufficient precision to be useful in human-population movement studies and uranium-thorium dating.

ICP-MS instruments

As indicated by its acronym, ICP-MS is a compound technique, consisting of an inductively coupled plasma connected to a mass spectrometer. Essentially, a sample is ionized initially within the plasma, and then the ions are separated and counted by the spectrometer. Plasma is a state of matter having no defining shape like a gas but consisting of atoms together with positively charged ions and free electrons. Its level of ionization allows it to respond to magnetic fields and conduct electricity. In ICP, an argon plasma is produced by seeding argon gas flowing through a quartz tube with electrons, which are accelerated with a radio-frequency generator. Collisions of some of the electrons with argon atoms yield more electrons, lost from argon atoms, and these electrons are themselves accelerated and then may collide with additional argon atoms, thus sustaining the plasma as long as the RF field is applied. The loss of electrons and their cyclical rejoining of other argon atoms in need of an electron repeat many times per second and generate extraordinary heat. Inductively coupled plasmas were first applied to atomic emission spectroscopy (AES) (Greenfield et al., 1964), the plasma being used to excite atoms in an injected sample, which then gave off light of characteristic wavelengths upon de-excitation. Not long after the advent of ICP-AES, it was recognized that argon plasmas, which produce temperatures in the 8,000–12,000° K range at their cores, are also excellent sources of positively charged ions. Once ionized, an atom can be identified as mass-to-charge ratio (m/e) by mass-spectrometric techniques.

In ICP-MS instruments, the ICP torch (which controls the flow of plasma) is oriented horizontally, and the stream of ions emerging from the torch is passed through an interface into a high vacuum environment conducive to measurement of mass-to-charge ratio. The interface usually consists of two nickel cones with small openings that allow passage of the ion beam from the torch while still maintaining a vacuum inside the mass spectrometer. Once under vacuum, ion optics focus the ion beam and remove stray photons and neutral species.

Measurement of ionic masses is usually accomplished by a device that filters the ion beam so that only particles

A.S. Gilbert (ed.), *Encyclopedia of Geoarchaeology*, DOI 10.1007/978-1-4020-4409-0,

with specific mass-to-charge ratio pass through and hit the ion detector. By far the most common mass filters are quadrupoles, which consist of four metal rods to which radio frequency and direct current voltages are applied. The specific settings of the RF and DC voltages determine which *m*/*e* ratios are “resonant,” meaning that they will pass down the central channel of the quadrupole and interact with the ion detector. By varying the voltages on the quadrupole, signal intensities for the masses of interest can be measured. The voltages can be changed extremely rapidly, such that the entire mass spectrum can be scanned in seconds.

Specific *m*/*e* particles can also be selectively measured with what are called magnetic sector ICP-MS instruments. In these instruments, the ion beam is directed into electrostatic and magnetic fields, which bend the beam as it travels toward the ion detector. The trajectories of heavier particles will be less affected by the fields than lighter particles, and the detector can thus be positioned so that only specific *m*/*e* particles reach the detector. Magnetic sector instruments can be adjusted to yield much greater mass resolution than quadrupole instruments, thus eliminating many interferences (see below).

Magnetic sector ICP-MS instruments with multiple ion detectors are called multicollector (MC)-ICP-MS. Multicollector (MC)-ICP-MS instruments are sector devices that permit sampling of ions from the plasma simultaneously through a series of faraday cups and discrete dynode electron multipliers (typically 12–15 faraday cups and 1–3 electron multipliers). The detector array is configured so that a range of up to about 16 atomic masses can be monitored simultaneously. This configuration is essentially the same as that used in thermal ionization mass spectrometer (TIMS) instruments, which historically have been the workhorses for isotope ratio analysis. MC-ICP-MS instruments are capable of determining isotope ratios with precisions comparable to those of TIMS but with far less sample preparation, since both liquid digestion and laser ablation (see below) are generally far less time-consuming than sample preparation for TIMS.

Another mass-spectrometric technique used in ICP-MS is time of flight (TOF). Rather than selectively counting particles with specific mass-to-charge ratios, as in quadrupole or magnetic sector ICP-MS, TOF instruments accelerate packets of ions from the ion beam into a flight tube, where they are reflected by an ion mirror (or reflectron) back toward a detector. The flight tube and reflectron are configured so that, by the time the packet arrives at the detector, distinct *m*/*e* ratios are separated with greater than 1 atomic mass unit (u) resolution, so that the smallest *m*/*e* ratios arrive first and all of them arrive before the next *m*/*e*. In the most common commercially available TOF-ICP-MS, 30,000 ion “pushouts” per second can be integrated up to 50 times per second, thus making the TOF much more effective at analyzing highly transient signals, such as from laser ablation (see below).

Interferences

All ICP-MS analyses are affected by interferences on masses that would otherwise be the best choices for determining the concentrations of elements of interest. The three types of interferences are isobaric, polyatomic (or molecular), and doubly charged ions.

Isobaric interferences refer to cases in which different elements have isotopes with the same mass. For example, a very minor isotope of calcium, ^{48}Ca, creates an isobaric interference on the major stable isotope of titanium, ^{48}Ti. Even though the isotopic abundance of ^{48}Ca is only 0.187 % in nature, compared to 73.72 % for ^{48}Ti, the easily ionized calcium may contribute significantly to the mass 48 peak if (as is often the case) the abundance of calcium in the sample is an order of magnitude (or more) higher than titanium. In this case, as with most other isobaric interferences, the appropriate resolution would be to choose another isotope of titanium for analysis, such as ^{47}Ti, which is 7.44 % abundant but does not suffer from problems of interference.

Polyatomic interferences are created by recombination of plasma-gas ions and ions from the sample matrix in cooler regions of the plasma. Argon, being a plasma gas, is a major contributor to polyatomic interferences. Besides the major argon isotope at mass 40, there are minor isotopes at mass 38 and mass 36. Combinations with oxygen (isotopes at masses 16, 17, and 18) then create seven potential polyatomic interferences ranging from mass 52 to mass 58.

Doubly charged ions have a *m*/*e* that is half of the corresponding singly charged ion. One of the most common interferences from a doubly charged ion is Ba^{++}. Doubly charged ^{38}Ba, for instance, creates an interference at mass 69, which is a major isotope of gallium. In general, doubly charged ions are less important than isobaric or polyatomic interferences because the first ionization potential of Ar is lower than the second ionization potential of most elements.

Sample preparation and introduction

As typically configured, ICP-MS instruments require samples to be introduced to the plasma torch as liquids. A peristaltic pump moves a solution containing the sample to a nebulizer, where it mixes with argon gas and becomes an aerosol. The nebulized sample usually passes through a spray chamber, which removes large droplets before the aerosol flows into the ICP torch. Liquid sample introduction poses a problem for applications in archaeology and geoarchaeology, since characterization is usually sought for inorganic solids, such as metals, lithics, ceramics, soils, and sediments.

One way to solve the liquid-sampling problem is to digest samples using an appropriate mix of acids and/or heat and/or pressure. Most metals can be digested in nitric and/or hydrochloric acid (Young and Pollard, 2000). Silicates, such as obsidian, flint, ceramics, and sediments, require more aggressive treatment involving hydrofluoric acid and microwave heating inside of Teflon bombs (e.g., Kennett et al., 2002). Once digested, samples are usually diluted in some combination of nitric acid and deionized water prior to injection in order to bring the solutions into the optimal range of the ICP-MS. Liquid standards (see below) are also prepared using the same liquid matrix. Some studies (e.g., Kennett et al., 2002; Little et al., 2004) have reported satisfactory correlation between results from digestion-ICP-MS analysis of ceramics and neutron activation analysis of the same materials. Nonetheless, the added time, trouble, and potential danger of silicate digestion are significant. In addition, small variations in sample preparation procedures and reagent quality together with the potential for contamination of very small digested samples can introduce subtle random and systematic effects that compromise the quality of the analytical data.

An alternative sample introduction approach that has seen increasing use over the past decade is laser ablation-ICP-MS. A typical LA-ICP-MS setup has a 213-nm Nd-YAG solid-state laser with either argon or helium flowing through the sample chamber, coupled to one of the ICP-MS instruments described above. More recently, UV excimer (exciplex) lasers with a wavelength of 193 nm have become available commercially. Samples are placed in the ablation chamber together with reference standards, and the chamber is purged of ambient gases. Software controls x-y-z movement of the ablation chamber and projects a video image of the inside of the chamber. Ablation patterns (lines, rasters, spots, or lines of spots) are drawn on the samples, and the characteristics of the ablation (spot size, scan speed, laser power, repetition rate, number of passes, and dwell time) are specified. When the ablation starts, material vaporized from the sample and ejected from the site of ablation is entrained in the gas stream flowing through the chamber. If helium is the ablation gas, the ablated aerosol joins an argon gas stream from the ICP-MS before the mixture flows into the argon plasma of the ICP torch.

Standardization

The raw output of an ICP-MS analysis consists of ion counts per unit of time or "signal intensities." Although signal intensity for a particular element obviously correlates with the amount of that element present in the sample, the nature of the correlation depends on instrument tuning, other elements present in the sample, reagents used for digestion, and other variable conditions. Converting signal intensities into elemental concentrations entails use of standards – materials with known concentrations of the elements of interest – to develop standard curves for a given batch of analyses.

For analysis of digested liquids, standard solutions are prepared in a graded series of concentrations from commercially available multielement standards. Ideally the standard concentrations will overlap and bracket the concentrations expected in the unknown solutions. The standards and the unknowns are also spiked with a known amount of an "internal standard," i.e., an element assumed absent in the unknowns and standards; signal intensities are then normalized prior to calibration in order to compensate for instrumental drift during the analysis.

Standardization in LA-ICP-MS is trickier than in solution ICP-MS. Since project-specific preparation of solid standards is usually impractical, the usual approach is to obtain solid standards with known concentrations of particular elements from the National Institute of Standards and Technology (NIST) or other sources. For silicates, NIST Glass Standard Reference Material (SRM) 610, 612, and 614 are widely used. Homogeneous natural materials, the main example being obsidian, are also used. Copper, brass, and bronze standards are also available from NIST.

Given an appropriate set of calibration standards, an additional problem in LA-ICP-MS involves selection of an internal standard for normalization of signal intensities. The concentration of an internal standard can sometimes be assumed. Obsidian, for instance, is rhyolitic volcanic glass, in which silicon concentrations remain very close to 35 %. Thus, silicon, monitored at the minor isotope mass 30 because of the high concentrations, can be used as the internal standard, with 35 % as the assumed concentration. Another approach to internal standardization involves independent determination of the concentrations of an appropriate analyte, for example, by electron microprobe or x-ray fluorescence, which then serves as the internal standard.

A third approach to internal standardization in LA-ICP-MS is applicable both to homogeneous matrices and to individual components of heterogeneous matrices, such as individual temper grains within a ceramic fabric. The approach was first proposed by Gratuze (1999; Gratuze et al., 2001) and has been adopted by several other groups utilizing LA-ICP-MS (Speakman and Neff, 2005; Neff, 2012a). It assumes that elements in silicate matrices are present as oxides, and therefore, once converted to oxide concentrations, the major, minor, and trace elements measured by LA-ICP-MS should sum to 100 %. The advantage of this approach is that the internal standard concentrations need not be known, since the standardized concentrations (ratios to internal standards) must sum to 100 %. The algebra involved is straightforward and has been spelled out by Gratuze (1999) and Neff (2012a), among others.

Applications of ICP-MS elemental analysis

As a highly sensitive, precise technique for elemental characterization, ICP-MS has potential in all of the application areas to which neutron activation analysis (NAA), x-ray fluorescence (XRF) analysis, ICP-AES, and other elemental techniques can be applied. These application areas include provenance determination, activity-area analysis, constructing paleoenvironmental records, and investigation of ancient technologies. With laser ablation, additional applications become possible, such as the provenance investigation of micro-artifacts as well as slips and pigments on ceramics.

Digestion-ICP-MS can be used in a manner analogous to other bulk elemental techniques, such as NAA, to investigate sources of raw materials used by past craftspeople. The premise on which such studies are based is sometimes called the provenance postulate (Weigand et al., 1977). This postulate holds that source determination is possible "as long as some qualitative or quantitative chemical or mineralogical difference exists between natural sources that exceeds the qualitative or quantitative variation within each source" (Neff, 2000, 107–108). Although standard practice is to assume that compositional subgroups of artifacts represent distinct sources, a better approach is to treat the assumption as a hypothesis and to rule out other possible causes of subgrouping tendencies, such as diagenesis or technological variation (Neff et al., 2003; Neff, 2012b).

ICP-MS provenance studies began appearing in the late 1990s. Early examples include the work of Mallory-Greenough et al. (1998) on Egyptian pottery; a comparison by Kennett et al. (2002) of ICP-MS and INAA results for Virgin Branch Anasazi pottery; a study by Kennett et al. (2004) of Lapita pottery; a study of Song Dynasty porcelains (Li et al., 2005); a study by Thornton et al. (2002) of copper alloys from Tepe Yahya, Iran; and a study by Hall et al. (1998) of gold artifacts from a Late Sarmatian burial (Russia). Other artifact classes analyzed by digestion-ICP-MS for provenance determination include obsidian (Bellot-Gurlet et al., 2008), steatite (Jones et al., 2007), basalt (Ma et al., 2011), and flint (Olofsson and Rodushkin, 2011). This is far from an exhaustive list, and readers are advised to scan recent issues of the *Journal of Archaeological Science* and *Archaeometry* for other examples.

Due to ease of sample preparation and its sensitivity to a wide range of elements, LA-ICP-MS has recently seen a surge in popularity for provenance research. As a result, many materials that can be analyzed easily by NAA, XRF, digestion-ICP-MS, or other bulk techniques are now being analyzed routinely by LA-ICP-MS. These include chert and flint (Speakman et al., 2002; Stevenson et al., 2009); obsidian (Tabares et al., 2005; Carballo et al., 2007); jade (Kovacevich et al., 2005; Neff et al., 2010); turquoise (Zedeño et al., 2005); quartzite (Pitblado et al., 2008); rhyolite (Scharlotta, 2010); historic glass trade beads from various world regions (Popelka et al., 2005; Dussubieux et al., 2008a); copper and copper alloys (Dussubieux, 2007; Dussubieux et al., 2008b); Bronze Age glass from Egypt, Greece, and Mesopotamia (Walton et al., 2009); gold (Guerra et al., 1999; Brostoff et al., 2009); and Maya blue pigment (Arnold et al., 2007, 2012). Beyond these applications, which essentially duplicate what could be done with bulk characterization, the microprobe possibilities of LA-ICP-MS have been exploited to characterize ceramic slips and pigments (Speakman and Neff, 2002, 2005; Neff, 2003; Vaughn et al., 2005; Cecil and Neff, 2006; Duwe and Neff, 2007; Backes et al., 2012), individual nonplastic particles within ceramic pastes (Larson et al., 2005; Neff and Sheets, 2005), clay matrices in ceramic pastes (Larson et al., 2005; Cochrane and Neff, 2006; Fitzpatrick et al., 2006; Beck and Neff, 2007; Dussubieux et al., 2007; Sharratt et al., 2009; Stoner and Glascock, 2012), and obsidian micro-debitage (Scharlotta et al., 2011).

The microprobe capabilities of LA-ICP-MS can sometimes provide crucial complementary evidence that clarifies or extends results from bulk-characterization provenance studies. One example is a recently published study of the fugitive hematite pigment on Olmec carved-gray and incised pottery from Mesoamerica (Backes et al., 2012). An earlier NAA study of Olmec pottery detected high-volume export of Olmec pots from the Gulf Coast heartland but no other Early Formative ceramic exchange (Blomster et al., 2005; Neff et al., 2006a; Neff et al., 2006b). Backes et al. (2012) used LA-TOF-ICP-MS in time-scan mode to detect highly transient signals produced during the ablation of hematite patches on Olmec gray pottery from two well-sampled sites: San Lorenzo, Veracruz (in the Olmec heartland), and Cantón Corralito, a putative Olmec outpost in southern Chiapas. Also included in the study were raw pigments found in archaeological contexts at both San Lorenzo and Cantón Corralito and geological hematite from the vicinity of San Lorenzo. Because the iron signal from hematite overwhelmed other components, Backes et al. utilized ratios of other analytes to iron in a pattern recognition analysis. The results of analysis of pigments from the pottery group and the raw pigments showed that the raw pigments had been exported from San Lorenzo and that carved-gray pots at Cantón Corralito, imports from both San Lorenzo and local copies, had been decorated with San Lorenzo-derived hematite. Based on these results, the Olmec not only exported vessels decorated with their unique symbolic system but also exported the raw materials necessary to recreate that symbolic system outside the Gulf Olmec heartland.

As a microprobe, LA-ICP-MS has also been useful in testing hypotheses about the nature of compositional subgroups identified in ceramic provenance research. For instance, Golitko et al. (2012) analyzed ceramics from the Sepik Coast of New Guinea at the Field Museum and found some clear associations between find spot and chemical group. However, some of the distinctions were based on variation in barium, an element suspected to be susceptible to diagenetic enrichment (Neff et al., 2003). In order to test this possibility, microscale mapping of elemental concentrations in Sepik Coast sherds was undertaken with LA-TOF-ICP-MS. Since barium showed enrichment near surfaces in high-barium specimens but no cross-sectional trend in low-barium specimens, postdepositional enrichment of barium could not be ruled out as an explanation for certain high-barium compositions. Elements other than barium also showed no trends across sherd cross sections (Golitko et al., 2012).

ICP-MS, like other elemental characterization techniques, can also be used in the investigation of sediments that are of interest in archaeology. Eastwood et al. (1998), for instance, identified the Santorini tephra from the 3,300 BP eruption of the Aegean Island of Thera in sediments from a small intramontane lake in Anatolia. In another example, Neff et al. (2006c) analyzed sediments from a 6-m wetland core extracted in Pacific coastal Guatemala and argued that patterns of elemental variation are partly attributable to variation in the intensity of chemical weathering on adjacent low hills. The resulting climate archive bears some striking similarities to other neotropical archives.

Spatial variation in archaeological sediment composition is often used as an indication of variation in past activities both on small geographic scales (activity-area analysis) and on larger scales (land-use history). ICP-MS, with its sensitivity to such a wide range of elements, is perhaps ideally suited for such studies. Entwistle and Abrahams (1997; Entwistle et al., 1998) carried out exploratory work and demonstrated both the potential and some of the limitations of ICP-MS for land-use analysis, and Wilson et al. (2008) carried out additional investigations of the linkages between soil chemistry and past activities (also see Wilson et al., 2009). Recent archaeological examples of ICP-MS-based activity-area studies include documentation of mercury and gold enrichment on Classic Maya floors (Cook et al., 2006), an ethnoarchaeological study of fish-processing areas in Alaska (Knudson and Frink, 2010), and investigation of intra-site organization in the Aleutian Islands (Misarti et al., 2011).

The diversity of applications of ICP-MS elemental analysis extends beyond the major categories mentioned above. Other applications include a study by Cucina et al. (2011) that used trace elements in human tooth enamel to identify foreigners in an archaeological burial assemblage, with infant teeth used as the baseline "local" compositional profile. In another set of studies, LA-ICP-MS-based "dendrochemistry" identified elemental signatures of volcanic eruptions in tree rings (Pearson et al., 2005, 2009). These examples by no means cover the full range of applications of ICP-MS elemental analysis in archaeology and geoarchaeology, and the near future will certainly see continued rapid growth in the number and diversity of such studies.

Applications of MC-ICP-MS isotope ratio characterization

The potential of ICP-MS isotope ratio analysis has been recognized for some time (Angelini et al., 1993; Tykot and Young, 1996; Young et al., 1996; Pingitore et al., 1997). Unfortunately, the limited precision achievable for most isotopic systems with these instruments has restricted their use. Lead isotopes are the exception to this rule, as demonstrated by one methodological investigation (Dudgeon et al., 2007) and several provenance studies of lead-based glaze paint on ceramics (Habicht Mauche et al., 2000, 2002; Huntley et al., 2007). Multicollector ICP-MS instruments offer much greater potential, both for isotope-based provenance investigations and for uranium-series dating, and one can anticipate that their use will predominate in isotope ratio work over the coming decade.

In the past, high-precision isotope ratio applications in archaeology and archaeometry have usually employed thermal ionization mass spectrometers (TIMS). Multicollector ICP-MS instruments are replacing TIMS instruments because both liquid digestion and laser ablation are far less time-consuming than sample preparation for TIMS. In addition, several studies (Baker et al., 2006; Fenn et al., 2009) have demonstrated that solution MC-ICP-MS results compare favorably with TIMS results for lead isotope ratio determination in archaeological materials. An additional advantage of MC-ICP-MS over TIMS is that due to the efficiency of ionization in the plasma source, MC-ICP-MS can be used to study both "traditional" (e.g., Sr, Nd, Pb, Hf) and "nontraditional" (e.g., Li, B, Be, Fe, Cu, Zn, Cr, S, Hg, Mo) isotope systems (Albarède and Beard, 2004).

MC-ICP-MS isotope ratio analysis is beginning to answer provenance questions that have proven difficult or impossible to address with elemental characterization. An ironic example concerns the provenance of artifacts of turquoise, which occurs naturally in association with copper ore deposits throughout the US Southwest (Thibodeau et al., 2012). The irony is that the provenance postulate, which holds that sourcing is possible if between-source differences exceed within-source variation (see above), was first stated in the context of a trace-element study of turquoise (Weigand et al., 1977), yet trace-element characterization has consistently failed to identify source-specific turquoise elemental fingerprints. In contrast, the recent work by Thibodeau et al. (2012) convincingly demonstrates that $^{87}Sr/^{86}Sr$ together with the isotope ratios of lead (^{204}Pb, ^{206}Pb, and ^{208}Pb), determined in this case by MC-ICP-MS, easily discriminate southwestern turquoise mines.

Another application of MC-ICP-MS isotope ratio characterization has been in studies of hominin mobility patterns. Analogous to the abovementioned trace-element study of Cucina et al. (2011), these studies assume that $^{87}Sr/^{86}Sr$ ratios in tooth enamel depend on their values in the local geological environment and that these values are fixed when the tooth is formed, whereas bone values change during an organism's lifetime. In a methodological study, Horstwood et al. (2008) report determinations of strontium isotopes in archaeological tooth enamel by LA-MC-ICP-MS and point out the need for careful attention to interferences from the calcium phosphate matrix. In another study, Richards et al. (2008) detected evidence of Neanderthal mobility via LA-MC-ICP-MS characterization of strontium isotope ratios in tooth enamel. Enamel values from a Neanderthal molar recovered from a coastal limestone environment in Greece were found to be consistent with more radiogenic (older) rocks and, thus, suggested that the individual had spent his/her childhood at least 20 km away from the coastal location. Nowell and Horstwood (2009) criticize this study for inadequate attention to interferences within the mass range of strontium isotopes. These charges were rebutted by Richards et al. (2009).

Finally, uranium-series dating of carbonates in speleothems and corals is currently being done primarily by MC-ICP-MS. Goldstein and Stirling (2003) describe the analytical protocols for solution MC-ICP-MS determination of isotopes in the ^{238}U decay chain, which need to be measured in U-series dating (see Bourdon et al. (2003) for theory of U-series dating). Eggins et al. (2005) and Hoffman et al. (2009) discuss the potential of laser ablation-MC-ICP-MS for in situ U-series dating. Applications of uranium-series dating important to archaeology and geoarchaeology include dating of early human remains (Pike and Pettitt, 2003), dating of corals in paleoclimate studies (Eggins et al., 2005; Potter et al., 2005), dating of corals incorporated into human constructions in Polynesia (Kirch and Sharp, 2005; Weisler et al., 2006), and high-resolution dating of speleothems in paleoclimate studies (Lachniet et al., 2012).

Conclusion

Over the past decade and a half, ICP-MS has become a - well-established elemental characterization technique in archaeological and geoarchaeological research. Provenance studies still probably make up the bulk of applications, but activity-area and land-use studies, dendrochemistry, population-movement studies, uranium-series dating, and other applications not yet invented will also comprise major areas of application over the coming decade.

Bibliography

Albarède, F., and Beard, B., 2004. Analytical methods for non-traditional isotopes. *Reviews in Mineralogy and Geochemistry*, **55**, 113–152.

Angelini, E., Atzeni, C., Bianco, P., Rosalbino, F., and Virdis, P. F., 1993. Lead isotope analysis of Nuragic bronzes and copper ores by ICP-MS. In Holland, G., and Eaton, A. N. (eds.), *Applications of Plasma Source Mass Spectrometry II*. Cambridge: Royal Society of Chemistry. Special Publication 124, pp. 165–174.

Arnold, D. E., Neff, H., Glascock, M. D., and Speakman, R. J., 2007. Sourcing the palygorskite used in Maya blue: a pilot study comparing the results of INAA and LA-ICP-MS. *Latin American Antiquity*, **18**(1), 44–58.

Arnold, D. E., Bohor, B. F., Neff, H., Feinman, G. M., Williams, P. R., Dussubieux, L., and Bishop, R., 2012. The first direct evidence of Pre-Columbian sources of palygorskite for Maya Blue. *Journal of Archaeological Science*, **39**(7), 2252–2260.

Backes, C., Cheetham, D., and Neff, H., 2012. The color of influence: a provenance study of hematite-based paints on early Olmec carved pottery. *Latin American Antiquity*, **23**(1), 70–92.

Baker, J., Stos, S., and Waight, T., 2006. Lead isotope analysis of archaeological metals by multiple-collector inductively coupled plasma mass spectrometry. *Archaeometry*, **48**(1), 45–56.

Beck, M. E., and Neff, H., 2007. Hohokam and Patayan interaction in southwestern Arizona: evidence from ceramic compositional analysis. *Journal of Archaeological Science*, **34**(2), 289–300.

Bellot-Gurlet, L., Dorighel, O., and Poupeau, G., 2008. Obsidian provenance studies in Colombia and Ecuador: obsidian sources revisited. *Journal of Archaeological Science*, **35**(2), 272–289.

Blomster, J. P., Neff, H., and Glascock, M. D., 2005. Olmec pottery production and export in ancient Mexico determined through elemental analysis. *Science*, **307**(5712), 1068–1072.

Bourdon, B., Turner, S., Henderson, G. M., and Lundstrom, C. C., 2003. Introduction to U-series geochemistry. *Reviews in Mineralogy and Geochemistry*, **52**(1), 1–21.

Brostoff, L. B., González, J. J., Jett, P., and Russo, R. E., 2009. Trace element fingerprinting of ancient Chinese gold with femtosecond laser ablation-inductively coupled mass spectrometry. *Journal of Archaeological Science*, **36**(2), 461–466.

Carballo, D. M., Carballo, J., and Neff, H., 2007. Formative and Classic Period obsidian procurement in central Mexico: a compositional study using laser ablation-inductively coupled plasma-mass spectrometry. *Latin American Antiquity*, **18**(1), 27–43.

Cecil, L. G., and Neff, N., 2006. Postclassic Maya slips and paints and their relationship to socio-political groups in El Petén, Guatemala. *Journal of Archaeological Science*, **33**(10), 1482–1491.

Cochrane, E. E., and Neff, H., 2006. Investigating compositional diversity among Fijian ceramics with laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS): implications for interaction studies on geologically similar islands. *Journal of Archaeological Science*, **33**(3), 378–390.

Cook, D. E., Kovacevich, B., Beach, T., and Bishop, R., 2006. Deciphering the inorganic chemical record of ancient human activity using ICP-MS: a reconnaissance study of late Classic soil floors at Cancuén, Guatemala. *Journal of Archaeological Science*, **33**(5), 628–640.

Cucina, A., Tiesler, V., Sierra Sosa, T., and Neff, H., 2011. Trace-element evidence for foreigners at a Maya port in Northern Yucatan. *Journal of Archaeological Science*, **38**(8), 1878–1885.

Dudgeon, J. V., Neff, H., Saint, A., and Balsanek, W., 2007. Evaluating the precision requirements for isotope ratio determination of archaeological materials using laser ablation–time-of-flight–inductively coupled plasma–mass spectrometry. In Glascock, M. D., Speakman, R. J., and Popelka-Filcoff, R. S. (eds.), *Archaeological Chemistry: Analytical Techniques and Archaeological Interpretation*. Washington, DC: American Chemical Society. ACS Symposium Series, Vol. 968, pp. 297–310.

Dussubieux, L., 2007. LA-ICP-MS analysis of copper alloy artifacts. In Glascock, M. D., Speakman, R. J., and Popelka-Filcoff, R. S. (eds.), *Archaeological Chemistry: Analytical Techniques and Archaeological Interpretation*. Washington, DC: American Chemical Society. ACS Symposium Series, Vol. 968, pp. 337–348.

Dussubieux, L., Golitko, M., Williams, P. R., and Speakman, J., 2007. Laser ablation-inductively coupled plasma-mass spectrometry analysis applied to the characterization of Peruvian Wari ceramics. In Glascock, M. D., Speakman, R. J., and Popelka-Filcoff, R. S. (eds.), *Archaeological Chemistry: Analytical Techniques and Archaeological Interpretation*. Washington, DC: American Chemical Society. ACS Symposium Series, Vol. 968, pp. 349–363.

Dussubieux, L., Deraisme, A., Frot, G., Stevenson, C., Creech, A., and Bienvenu, Y., 2008a. LA-ICP-MS, SEM-EDS and EPMA analysis of Northeastern American copper-based artifacts: impact of corrosion and heterogeneity on the reliability of LA-ICP-MS compositional results. *Archaeometry*, **50**(4), 643–657.

Dussubieux, L., Kusimba, C. M., Gogte, V., Kusimba, S. B., Gratuze, B., and Oka, R., 2008b. The trading of ancient glass beads: new analytical data from South Asian and East African soda-alumina glass beads. *Archaeometry*, **50**(5), 727–821.

Duwe, S., and Neff, H., 2007. Glaze and slip pigment analysis of Pueblo IV period ceramics from east-central Arizona using time of flight-laser ablation-inductively coupled plasma-mass spectrometry (TOF-LA-ICP-MS). *Journal of Archaeological Science*, **34**(3), 403–414.

Eastwood, W. J., Pearce, N. J. G., Westgate, J. A., and Perkins, W. T., 1998. Recognition of Santorini (Minoan) tephra in lake sediments from Gölhisar Gölü, southwest Turkey by laser ablation ICP-MS. *Journal of Archaeological Science*, **25**(7), 677–687.

Eggins, S. M., Grün, R., McCulloch, M. T., Pike, A. W. G., Chappell, J., Kinsley, L., Mortimer, G., Shelley, M., Murray-Wallace, C. V., Spötl, C., and Taylor, L., 2005. In situ U-series dating by laser-ablation multi-collector ICPMS: new prospects for Quaternary geochronology. *Quaternary Science Reviews*, **24**(23–24), 2523–2538.

Entwistle, J. A., and Abrahams, P. W., 1997. Multi-element analysis of soils and sediments from Scottish historical sites. The potential of inductively coupled plasma-mass spectrometry for rapid site investigation. *Journal of Archaeological Science*, **24**(5), 407–416.

Entwistle, J. A., Abrahams, P. W., and Dodgshon, R. A., 1998. Multi-element analysis of soils from Scottish historical sites. Interpreting land-use history through the physical and geochemical analysis of soil. *Journal of Archaeological Science*, **25**(1), 53–68.

Fenn, T., Robertshaw, P., Wood, M., and Chesley, J., 2009. Early Islamic commerce with sub-Saharan Africa: chemical and isotopic analyses of late 1st millennium A.D. glass beads from Igbo-Ukwu, Nigeria. Paper presented at the 2009 SAA Meetings, Atlanta, April 26, 2009.

Fitzpatrick, S. M., Takamiya, H., Neff, H., and Dickenson, W. R., 2006. Compositional analysis of Yayoi-Heian period ceramics from Okinawa: examining the potential for provenance study. *Geoarchaeology*, **21**(8), 803–822.

Goldstein, S. J., and Stirling, C. H., 2003. Techniques for measuring uranium-series nuclides: 1992–2002. *Reviews in Mineralogy and Geochemistry*, **52**(1), 23–57.

Golitko, M., Dudgeon, J. V., Neff, H., and Terrell, J. E., 2012. Identification of post-depositional chemical alteration of ceramics from the north coast of Papua New Guinea (Sanduan Province) by time-of-flight–laser ablation–inductively coupled plasma–mass spectrometry (TOF-LA-ICP-MS). *Archaeometry*, **54**(1), 80–100.

Gratuze, B., 1999. Obsidian characterization by laser ablation ICP-MS and its application to prehistoric trade in the Mediterranean and the Near East: sources and distribution of obsidian within the Aegean and Anatolia. *Journal of Archaeological Science*, **26**(8), 869–881.

Gratuze, B., Blet-Lemarquard, M., and Barrandon, J.-N., 2001. Mass spectrometry with laser sampling: a new tool to characterize archaeological materials. *Journal of Radioanalytical and Nuclear Chemistry*, **247**(3), 645–656.

Greenfield, S., Jones, I. L., and Berry, C. T., 1964. High-pressure plasmas as spectroscopic emission sources. *Analyst*, **89**(1064), 713–720.

Guerra, M. F., Sarthre, C.-O., Gondonneau, A., and Barrington, J.-N., 1999. Precious metal and provenance enquiries using LA-ICP-MS. *Journal of Archaeological Science*, **26**(8), 1101–1110.

Habicht-Mauche, J. A., Glenn, S. T., Milford, H., and Flegal, A. R., 2000. Isotopic tracing of prehistoric Rio Grande glaze-paint production and trade. *Journal of Archaeological Science*, **27**(8), 709–713.

Habicht-Mauche, J. A., Glenn, S. T., Schmidt, M. P., Franks, R., Milford, H., and Flegal, A. R., 2002. Stable lead isotope analysis of Rio Grande glaze paints and ores using ICP-MS: a comparison of acid dissolution and laser ablation techniques. *Journal of Archaeological Science*, **29**(9), 1043–1053.

Hall, M. E., Brimmer, S. P., Li, F.-H., and Yablonsky, L., 1998. ICP-MS and ICP-OES studies of gold from a late Sarmatian burial. *Journal of Archaeological Science*, **25**(6), 545–552.

Hoffman, D. L., Spötl, C., and Mangini, A., 2009. Micromill and in situ laser ablation sampling techniques for high spatial resolution MC-ICPMS U-Th dating of carbonates. *Chemical Geology*, **259** (3–4), 253–261.

Horstwood, M. S. A., Evans, J. A., and Montgomery, J., 2008. Determination of Sr isotopes in calcium phosphates using laser ablation inductively coupled plasma mass spectrometry and their application to archaeological tooth enamel. *Geochimica et Cosmochimica Acta*, **72**(23), 5659–5674.

Huntley, D. L., Spielmann, K. A., Habicht-Mauche, J. A., Herhahn, C. L., and Flegal, A. R., 2007. Local recipes or distant commodities? Lead isotope and chemical compositional analysis of glaze paints from the Salinas pueblos, New Mexico. *Journal of Archaeological Science*, **34**(7), 1135–1147.

Jones, R. E., Kilikoglou, V., Olive, V., Bassiakos, Y., Ellam, R., Bray, I. S. J., and Sanderson, D. C. W., 2007. A new protocol for the chemical characterisation of steatite – two case studies in Europe: the Shetland Islands and Crete. *Journal of Archaeological Science*, **34**(4), 626–641.

Kennett, D. J., Sakai, S., Neff, H., Gossett, R., and Larson, D. O., 2002. Compositional characterization of prehistoric ceramics: a new approach. *Journal of Archaeological Science*, **29**(5), 443–455.

Kennett, D. J., Anderson, A. J., Cruz, M. J., Clark, G. R., and Summerhayes, G. R., 2004. Geochemical characterization of Lapita pottery via inductively coupled plasma-mass spectrometry (ICP-MS). *Archaeometry*, **46**(1), 35–46.

Kirch, P. V., and Sharp, W. D., 2005. Coral ^{230}Th dating of the imposition of a ritual control hierarchy in precontact Hawaii. *Science*, **307**(5706), 102–104.

Knudson, K. J., and Frink, L., 2010. Ethnoarchaeological analysis of arctic fish processing: chemical characterization of soils on Nelson Island, Alaska. *Journal of Archaeological Science*, **37**(4), 769–783.

Kovacevich, B., Neff, H., and Bishop, R. L., 2005. Laser ablation-ICP-MS chemical characterization of jade from a jade workshop at Cancuen, Guatemala. In Speakman, R. J., and Neff, H. (eds.), *Laser Ablation ICP-MS in Archaeological Research*. Albuquerque: University of New Mexico Press, pp. 39–56.

Lachniet, M. S., Bernal, J. P., Asmerom, Y., Polyak, V., and Piperno, D., 2012. A 2400 yr Mesoamerican rainfall reconstruction links climate and cultural change. *Geology*, **40**(3), 259–262.

Larson, D. O., Sakai, S., and Neff, H., 2005. Laser ablation inductively coupled plasma-mass spectrometry (LA-ICP-MS) as a bulk chemical characterization technique: comparison of LA-ICP-MS, digestion ICP-MS, and INAA data on Virgin Branch Anasazi ceramics. In Speakman, R. J., and Neff, H. (eds.), *Laser Ablation ICP-MS in Archaeological Research*. Albuquerque: University of New Mexico Press, pp. 95–103.

Li, B.-P., Greig, A., Zhao, J.-X., Collerson, K. D., Quan, K.-S., Meng, Y.-H., and Ma, Z.-L., 2005. ICP-MS trace element analysis of Song dynasty porcelains from Ding, Jiexiu and Guantai kilns, north China. *Journal of Archaeological Science*, **32**(2), 251–259.

Little, N. C., Kosakowsky, L. J., Speakman, R. J., Glascock, M. D., and Lohse, M. D., 2004. Characterization of Maya pottery by INAA and ICP-MS. *Journal of Radioanalytical and Nuclear Chemistry*, **262**(1), 103–110.

Ma, J., Bolhar, R., Weisler, M. I., Feng, Y., and Zhao, J., 2011. Reproducibility of elemental analyses of basaltic stone artefacts by quadrupole ICP-MS using different sample sizes and digestion methods, with implications for archaeological research. *Archaeometry*, **53**(5), 890–899.

Mallory-Greenough, L. M., Greenough, J. D., and Owen, J. V., 1998. New data for old pots: trace-element characterization of ancient Egyptian pottery using ICP-MS. *Journal of Archaeological Science*, **25**(1), 85–97.

Misarti, N., Finney, B. P., and Maschner, H., 2011. Reconstructing site organization in the eastern Aleutian Islands, Alaska using multi-element chemical analysis of soils. *Journal of Archaeological Science*, **38**(7), 1441–1455.

Neff, H., 2000. Neutron activation analysis for provenance determination in archaeology. In Ciliberto, E., and Spoto, G. (eds.), *Modern Analytical Methods in Art and Archaeology*. New York: Wiley, pp. 81–134.

Neff, H., 2003. Analysis of Mesoamerican plumbate pottery surfaces by laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS). *Journal of Archaeological Science*, **30**(1), 21–35.

Neff, H., 2012a. Laser ablation ICP-MS in archaeology. In Lee, M. S. (ed.), *Mass Spectrometry Handbook*. Hoboken: Wiley, pp. 829–843.

Neff, H., 2012b. Comment: chemical and mineralogical approaches to ceramic provenance determination. *Archaeometry*, **54**(2), 244–249.

Neff, H., and Sheets, P., 2005. Archaeological applications of tephra analysis by LA-ICP-MS. In Speakman, R. J., and Neff, H. (eds.), *Laser Ablation ICP-MS in Archaeological Research*. Albuquerque: University of New Mexico Press, pp. 117–123.

Neff, H., Cogswell, J. W., and Ross, L. M., Jr., 2003. Supplementing bulk chemistry in archaeological ceramic provenance investigations. In van Zelst, L. (ed.), *Patterns and Process: Essays in Honor of Dr. Edward V. Sayre*. Suitland: Smithsonian Center for Materials Research and Education, pp. 201–224.

Neff, H., Blomster, J., Glascock, M. D., Bishop, R. L., Blackman, M. J., Coe, M. D., Cowgill, G. L., Cyphers, A., Diehl, R. A., Houston, S., Joyce, A. A., Lipo, C. P., and Winter, M., 2006a. Smokescreens in the provenance investigation of early formative Mesoamerican ceramics. *Latin American Antiquity*, **17**(1), 104–118.

Neff, H., Blomster, J. P., Bishop, R. L., Blackman, M. J., Coe, M. D., Cowgill, G. L., Diehl, R. A., Houston, S., Joyce, A. A., Lipo, C. P., Stark, B. L., and Winter, M., 2006b. Methodological issues in the provenance investigation of early formative Mesoamerican ceramics. *Latin American Antiquity*, **17**(1), 54–76.

Neff, H., Pearsall, D. M., Jones, J. G., Arroyo de Pieters, B., and Freidel, D. E., 2006c. Climate change and population history in the Pacific Lowlands of southern Mesoamerica. *Quaternary Research*, **65**(3), 390–400.

Neff, H., Kovacevich, B., and Bishop, R. L., 2010. Caracterización de los compuestos de la jadeíta mesoamericana: Breve revisión a partir de los resultados obtenidos durante el estudio de la máscara de K'inich Janaab' Pakal. In Filloy Nadal, L. (ed.), *Misterios de un rostro maya: La máscara funeraria de K'inich Janaab' Pakal de Palenque*. México: Instituto Nacional de Antropología e Historia, pp. 131–138.

Nowell, G. M., and Horstwood, M. S. A., 2009. Comments on Richards et al., Journal of Archaeological Science 35, 2008 "Strontium isotope evidence of Neanderthal mobility at the site of Lakonis, Greece using laser-ablation PIMMS. *Journal of Archaeological Science*, **36**(7), 1334–1341.

Olofsson, A., and Rodushkin, I., 2011. Provenancing flint artefacts with ICP-MS using REE signatures and Pb isotopes as discriminants: preliminary results of a case study from northern Sweden. *Archaeometry*, **53**(6), 1142–1170.

Pearson, C. L., Manning, S. W., Coleman, M. L., and Jarvis, K. E., 2005. Can tree-ring chemistry reveal absolute dates for past volcanic eruptions? *Journal of Archaeological Science*, **32**(8), 1265–1274.

Pearson, C. L., Dale, D. S., Brewer, P. W., Kuniholm, P. I., Lipton, J., and Manning, S. W., 2009. Dendrochemical analysis of a tree-ring growth anomaly associated with the Late Bronze Age eruption of Thera. *Journal of Archaeological Science*, **36**(6), 1206–1214.

Pike, A. W. G., and Pettitt, P. B., 2003. U-series dating and human evolution. *Reviews in Mineralogy and Geochemistry*, **52**(1), 607–630.

Pingitore, N. E., Jr., Leach, J. D., Villalobos, J., Peterson, J. A., and Hill, D., 1997. Provenance determination from ICP-MS elemental and isotopic compositions of El Paso area ceramics. In Vandiver, P. B., Druzik, J. R., Merkel, J. F., and Stewart, J. (eds.), *Materials Issues in Art and Archaeology V*. Pittsburgh: Materials Research Society. Materials Research Society Symposium Proceedings 462, pp. 59–70.

Pitblado, B. L., Dehler, C., Neff, H., and Nelson, S. T., 2008. Pilot study experiments sourcing quartzite, Gunnison Basin, Colorado. *Geoarchaeology*, **23**(6), 742–778.

Popelka, R. S., Glascock, M. D., Robertshaw, P., and Wood, M., 2005. Laser ablation-ICP-MS of African glass trade beads. In Speakman, R. J., and Neff, H. (eds.), *Laser Ablation ICP-MS in Archaeological Research*. Albuquerque: University of New Mexico Press, pp. 84–93.

Potter, E.-K., Stirling, C. H., Wiechert, U. H., Halliday, A. N., and Spötl, C., 2005. Uranium-series dating of corals in situ using laser-ablation MC-ICPMS. *International Journal of Mass Spectrometry*, **240**(1), 27–35.

Richards, M., Harvati, K., Grimes, V., Smith, C., Smith, T., Hublin, J.-J., Karkanas, P., and Panagopoulou, E., 2008. Strontium isotope evidence of Neanderthal mobility at the site of Lakonis, Greece using laser-ablation PIMMS. *Journal of Archaeological Science*, **35**(5), 1251–1256.

Richards, M., Grimes, V., Smith, C., Smith, T., Harvati, K., Hublin, J.-J., Karkanas, P., and Panagopoulou, E., 2009. Response to Nowell and Horstwood (2009). *Journal of Archaeological Science*, **36**(7), 1657–1658.

Scharlotta, I., 2010. Groundmass microsampling using laser ablation time-of-flight inductively coupled plasma mass spectrometry (LA-TOF-ICP-MS): potential for rhyolite provenance research. *Journal of Archaeological Science*, **37**(8), 1929–1941.

Scharlotta, I., Gilstrap, W., and Neff, H., 2011. No stone unburned: a compositional analysis of obsidian microdebitage by laser ablation TOF-ICP-MS. *Archaeometry*, **53**(5), 873–889.

Sharratt, N., Golitko, M., Williams, P. R., and Dussubieux, L., 2009. Ceramic production during the Middle Horizon: Wari and Tiwanaku clay procurement in the Moquegua Valley, Peru. *Geoarchaeology*, **24**(6), 792–820.

Speakman, R. J., and Neff, H., 2002. Evaluation of painted pottery from the Mesa Verde region using laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS). *American Antiquity*, **67**(1), 137–144.

Speakman, R. J., and Neff, H., 2005. The application of laser ablation-ICP-MS to the study of archaeological materials—an introduction. In Speakman, R. J., and Neff, H. (eds.), *Laser Ablation ICP-MS in Archaeological Research*. Albuquerque: University of New Mexico Press, pp. 1–15.

Speakman, R. J., Neff, H., Glascock, M. D., and Higgins, B. J., 2002. Characterization of archaeological materials by laser ablation-inductively coupled plasma-mass spectrometry. In Jakes, K. A. (ed.), *Archaeological Chemistry: Materials, Methods, and Meaning*. Washington, DC: American Chemical Society. ACS Symposium Series, Vol. 831, pp. 48–63.

Stevenson, C. M., Bikowski, E., Neff, H., Orliac, M., and Pendleton, C., 2009. Investigations into the European provenance of historic gunflints from Fort Christanna, Virginia, through trace element chemistry. *Archaeology of Eastern North America*, **35**, 49–62.
Stoner, W. D., and Glascock, M. D., 2012. The forest or the trees? Behavioral and methodological considerations for geochemical characterization of heavily-tempered ceramic pastes using NAA and LA-ICP-MS. *Journal of Archaeological Science*, **39**(8), 2668–2683.
Tabares, A. N., Love, M. W., Speakman, R. J., Neff, H., and Glascock, M. D., 2005. Straight from the source: obsidian prismatic blades at El Ujuxte, Guatemala. In Speakman, R. J., and Neff, H. (eds.), *Laser Ablation ICP-MS in Archaeological Research*. Albuquerque: University of New Mexico Press, pp. 17–28.
Thibodeau, A. M., Chesley, J. T., Ruiz, J., Killick, D. J., and Arthur Vokes, A., 2012. An alternative approach to the prehispanic turquoise trade. In King, J. C. H., Carocci, M., Cartwright, C., McEwan, C., and Stacey, R. (eds.), *Turquoise in Mexico and North America. Science, Conservation, Culture, and Collections*. London: Archetype and British Museum, pp. 65–74.
Thornton, C. P., Lamberg-Karlovsky, C. C., Liezers, M., and Young, S. M. M., 2002. On pins and needles: tracing the evolution of copper-base alloying at Tepe Yahya, Iran, via ICP-MS analysis of common-place items. *Journal of Archaeological Science*, **29**(12), 1451–1460.
Tykot, R. H., and Young, S. M. M., 1996. Archaeological applications of inductively coupled plasma-mass spectrometry. In Orna, M. V. (ed.), *Archaeological Chemistry: Organic, Inorganic, and Biochemical Analysis*. Washington, DC: American Chemical Society. ACS Symposium Series, Vol. 625, pp. 116–130.
Vaughn, K. J., Conlee, C. A., Neff, H., and Schreiber, K. J., 2005. A compositional analysis of Nasca polychrome paints: implications for craft production on the pre-Hispanic south coast of Peru. In Speakman, R. J., and Neff, H. (eds.), *Laser Ablation ICP-MS in Archaeological Research*. Albuquerque: University of New Mexico Press, pp. 138–154.
Walton, M. S., Shortland, A., Kirk, S., and Degryse, P., 2009. Evidence for the trade of Mesopotamian and Egyptian glass to Mycenaean Greece. *Journal of Archaeological Science*, **36**(7), 1496–1503.
Weigand, P. C., Harbottle, G., and Sayre, E. V., 1977. Turquoise sources and source analysis: Mesoamerica and the Southwestern U.S.A. In Earle, T. K., and Ericson, J. E. (eds.), *Exchange Systems in Prehistory*. New York: Academic, pp. 15–34.
Weisler, M. I., Collerson, K. D., Feng, Y.-X., Zhao, J.-X., and Yu, K.-F., 2006. Thorium-230 coral chronology of a late prehistoric Hawaiian chiefdom. *Journal of Archaeological Science*, **33**(2), 273–282.
Wilson, C. A., Davidson, D. A., and Cresser, M. S., 2008. Multi-element soil analysis: an assessment of its potential as an aid to archaeological interpretation. *Journal of Archaeological Science*, **35**(2), 412–424.
Wilson, C. A., Davidson, D. A., and Cresser, M. S., 2009. An evaluation of the site specificity of soil elemental signatures for identifying and interpreting former functional areas. *Journal of Archaeological Science*, **36**(10), 2327–2334.
Young, S. M. M., and Pollard, A. M., 2000. Atomic spectroscopy and spectrometry. In Ciliberto, E., and Spoto, G. (eds.), *Modern Analytical Methods in Art and Archaeology*. New York: Wiley, pp. 21–53.
Young, S. M. M., Phillips, D. A., Jr., and Mathien, F. J., 1996. Lead isotope analysis of turquoise sources in the southwestern U.S.A. and Mesoamerica: a preliminary report. In Demirci, S., Demirci, S., Özer, A. M., and Summers, G. D. (eds.), *Archaeometry 94: The Proceedings of the 29th International Symposium on Archaeometry, Ankara, 9–14 May 1994*. Ankara: TÜBİTAK, pp. 147–150.
Zedeño, M. N., Neff, H., and Nielsen, A., 2005. Searching for analytical alternatives to the characterization of copper minerals. In Speakman, R. J., and Neff, H. (eds.), *Laser Ablation ICP-MS in Archaeological Research*. Albuquerque: University of New Mexico Press, pp. 77–83.

Cross-references

Anthrosols
Ceramics
Geochemical Sourcing
Lead Isotopes
Lithics
Living Surfaces
Metals
Neutron Activation Analysis
Paleoenvironmental Reconstruction
Petrography
Pigments
Speleothems
Strontium Isotopes
U-Series Dating
X-ray Fluorescence (XRF) Spectrometry in Geoarchaeology

INUNDATED FRESHWATER SETTINGS

Jessi J. Halligan
Department of Anthropology, Florida State University, Tallahassee, FL, USA

Synonyms

Freshwater archaeology; Inundated terrestrial sites; Submerged prehistoric sites; Submerged terrestrial sites

Definitions

Base level: the imaginary line below which a river or stream can no longer erode. In coastal and near coastal areas, this is approximately sea level, but inland and in man-made reservoir systems, it can be quite different.

Karst: landscape formed by the dissolution of carbonates (limestones and dolomites, commonly) characterized by porous surface topography including sinkholes (more formally known as dolines), caves, and interrupted surface water flow with common underground stream flow.

Prehistoric: the generic archaeological term referring to the period before written records in a given area.

Submergence: the process by which a terrestrial site becomes inundated (or submerged), during which the site is most at danger for destruction.

Terrestrial: on land, especially in reference to sites that were created on dry land that are currently underwater.

Introduction

Prior to the Industrial Revolution, access to fresh drinking water was one of the most important considerations for human settlement. Unsurprisingly, the overwhelming majority of human habitation from the earliest hominin sites to modern cities was located very near water sources, which means a very large percentage of potential archaeological sites is likewise located near water sources, ancient and extant historical. This entry specifically deals with the geoarchaeology of submerged freshwater sites, as well as the site formation processes, preservation potential, and exploration of sites that can be found beneath freshwaters. Other entries on submerged continental shelves, coastal settings, and paleoshores discuss these matters for coastal environments or areas that became coastal environments, and the entry on alluvial settings discusses site formation processes in formerly wet areas that become desiccated and for settings adjacent to rivers.

Geological background: site formation processes and site preservation potential

Throughout the Pleistocene and Holocene, thousands of archaeological sites were submerged by oceans, rivers, and lakes. Most of these sites, however, were destroyed by scouring river channels with turbulent water flows, nearshore wave processes, and storm surge. In certain rare situations, some of these sites or portions of them have survived.

The world changed a great deal during the closing millennia of the Pleistocene and early Holocene, especially in the Northern Hemisphere. From approximately 18,000–5,000 radiocarbon years ago, global sea levels rose more than 120 m (Blum and Törnqvist, 2000; Balsillie and Donoghue, 2004; Peltier and Fairbanks, 2006; Milliken et al., 2008; Harris et al., 2013) due to massive influxes of glacial meltwater. As the glaciers melted, enormous channels were scoured by the meltwater, which created and reshaped many inland rivers such as the St. Lawrence, Mississippi, Missouri, Columbia, and Hudson drainage systems in North America. The North American Great Lakes were also created from larger glacial lakes. At the same time, the land surface itself was slowly rising because it was no longer being compressed by the weight of millions of tons of ice. This process, known as isostatic rebound, caused major topographic changes, which, in turn, caused dramatic changes in stream patterns and lake levels. Dramatic landform change also occurred due to the deposition of glacial loess (wind-borne sediment) in many northern latitudes.

As the meltwater began to refill the ocean basins, enormous swathes of land were submerged on the continental shelves, former rivers and streams were drowned, and the base level of all but the most interior rivers and streams rose in response. This rise in base level is especially significant to the discussion of freshwater site preservation, as many rivers dramatically changed shape in response. Specifically, many rivers concurrently began to infill former channels and switched from braided to meandering stream systems, especially on the coastal plains of the world (Leigh, 2008; Harris et al., 2013). This would have led to obliteration of some sites as terraces were destroyed by channel formation, yet there was deeply buried terrestrial preservation of some sites on abandoned terraces and, very rarely, preservation or partial preservation of other sites within river channels. Descriptions of flow types and processes that are found in meandering stream systems can be found in classic discussions of fluvial geomorphology (Wolman and Miller, 1960; Schumm, 1973).

The aforementioned rise in base level, increased surface water availability, and the generally warmer climate of the Holocene allowed thousands of lakes to form in the postglacial landscape. Many formed in features previously carved by glaciers or caused by glacial outwash in northern latitudes, but numerous lakes formed in non-glaciated areas as well. As a large percentage of the lakes increased in area throughout the Holocene, most sites created by people living on lakeshores late in the Pleistocene or early in the Holocene would have been inundated. Occasionally, these sites were preserved under the right conditions, generally when they were buried (especially in marshy deposits) before full submergence, or when they were transgressed quickly and then buried while newly submerged.

Talbot (2005) offers an excellent introductory discussion of the sedimentation processes within freshwater lakes. In general, sedimentation within lakes is strongly controlled by river inlets and outlets, and this means that the possibilities for buried sites will also usually be controlled by these rivers. Protected inlets where sediment can accumulate, rather than areas directly impacted by fluvial processes, are generally more likely to inundate in a way that would gently preserve sites. Sonnenburg et al. (2011), for instance, have discovered microdebitage in early Holocene peaty sediments in Rice Lake (Ontario) that were located in a shallow marshy lagoon adjacent to the main lake body. Mazurkevich and Dolbunova (2011) report numerous well-preserved mid-Holocene villages that were built on lakeside marshes and later inundated in northern Russia.

Man-made lakes also contain recently inundated freshwater sites. In the mid-twentieth century, thousands of dams were built for hydroelectric power, water reservoirs, and floodwater control all over the world (Graf, 2005). Many of these man-made reservoirs created large lakes out of former tiny streams. Over time, these artificial basins become infilled with sediment, as there is little to no flow through them, so sites on the former river terraces become flooded, then buried, which has led most likely to the destruction of the majority of them. A few sites preserved remarkably well. For instance, there are preserved towns under the waters of the St. Lawrence Seaway, Smith Mountain Lake, and the Oahe Reservoir, to name only a few, all regularly discussed on SCUBA diver fora. Though the prehistoric site potential of these reservoirs has been little explored, Hooge (2013) provides an excellent overview of the challenges and potentials through the study of Spring Lake in Texas. This untested potential is quite good in other reservoirs. Prior to dam construction, many prehistoric archaeological sites were partially excavated to salvage data. Some of these sites were well-preserved rock-shelters prior to flooding, such as Marmes Rockshelter in Washington state (Hicks, 2004). It is possible that the rapid flooding following dam closure would have allowed shelters to be rapidly submerged, infilling them with sediment, and preserving the site within, although this has not yet been tested.

In humid karstic environments, such as can be found in the Yucatan Peninsula, the Bahamas, and Florida, hydrology is a very complex process. Stream flow often abruptly disappears underground and reappears suddenly, and the terrestrial landscape and river bottoms alike are commonly pocked with sinkholes. This is due to the fractured and porous bedrock that causes very complex movements of groundwater. Karst settings have proven to be remarkable for preserving submerged archaeological sites of all kinds. In the Yucatan Peninsula, submerged karst features contain evidence of extinct fauna, many of the oldest human remains in the Americas, and the famous Mayan cenotes, which are not submerged sites in the traditional sense as people were deliberately depositing materials into the water (Leshikar-Denton and Luna Erreguerena, 2008; Chatters et al., 2014). In Florida, hundreds of Paleoindian artifacts dating to the late Pleistocene have been discovered within sinkholes in the bottom of karstic streams. Many of these artifacts are made of bone or ivory, some of which have been preserved well enough for direct dating, which is extremely rare for artifacts of this age (Hemmings, 1999; Balsillie et al., 2006; Webb, 2006; Dunbar, 2012). Many of these sinkholes have acted as sediment traps, containing equally well-preserved peats, soils, and sediments that contain excellent paleoenvironmental records from the late Pleistocene and Holocene. Some of the archaeological materials within these sinkhole deposits are associated with soils that formed during periods of terrestrial exposure and were thus available for people to utilize (Halligan, 2012).

In sum, very few archaeological sites probably survived inundation. The fluvial submergence process is not gentle. When rivers transgress new areas, flows are often turbulent, and much geomorphic work is likely to be done, destroying sites and redepositing their sediments along the way. Further, relatively few rivers maintain the same channel for long periods of time; as rivers meander through their floodplain, a site that is submerged in one century is likely to be exposed the next and possibly eroded in the following. In the case of freshwater lakes, shorelines are very often also quite turbulent and erosive, at least on a semiannual basis. This means that nearshore sediments are frequently reworked, so unless the site is submerged very rapidly and spends almost no time in the nearshore zone, artifacts are likely to be redeposited and features destroyed. Karstic systems and freshwater marshes have the best potential for long-term preservation due to relative landscape stability, but the discontinuous nature of streams in karst settings means that each portion of a karst river and each sink will have somewhat different preservation potential.

Freshwater shipwrecks may be exceptions to some or all of these general preservation rules. If a vessel sinks in cold deep water, it can preserve extraordinarily well if the water is fresh as it is below the reach of most geomorphic processes and is largely below biotic activity as well. There are a number of such vessels that have been recorded in the Great Lakes of North America (Crisman, 2014a) such as the *Hamilton* and *Scourge*, both of which had been preserved almost undamaged since 1812 until recent invasions by mussels. Vessels sunken in lakes may settle into bottom sediments for millennia (Wheeler et al., 2003), and wrecks in rivers may be submerged, buried, and re-exposed (Crisman, 2014b).

Inundated site preservation in all environments is most likely when sediment loads are relatively large and fine-grained so the site is buried before submergence and when the site is protected from the direct effects of turbulent flow even during major geomorphic events. Rapid burial, rapid inundation, and constant moisture all acting together increase organic preservation and the likelihood of in situ deposits as well. This confluence of geomorphic events is likely to be a relatively local process, which means site preservation would have been a local process as well, so fine-grained analyses are especially important when looking for inundated freshwater sites.

Location and excavation

Because site preservation will happen only in relatively rare exceptions, locating inundated freshwater sites requires either (1) precise modeling of broadscale geomorphic processes that are applied to rigorous models of human behavior to determine where people *may* have been or (2) sites must be located by chance. The corollary of site preservation is site visibility, which has two aspects: site complexity and site exposure. If a site was larger, more complex, and occupied for a long period of time, which are often related attributes, it is more likely to be at least partially preserved than a smaller site in the same setting. If it were to preserve, it also would be much more likely to be encountered by archaeologists for two main reasons. First, there is more of it, so testing strategies are more likely to encounter it. Second, complex, long-occupied sites are much easier to model on a landscape because the factors that made an area attractive for settlement are more predictable in this case. Site exposure (literally, site visibility) often means that a site is poorly preserved. Sites preserve best when they are buried in sediment before being inundated. If artifacts remain on the surface, they are very likely to become reworked into secondary contexts, just like surface artifacts on terrestrial sites. However, sometimes only a portion of a site has been exposed, which is how most underwater localities have been located. Sites that have been buried and protected may have excellent preservation, but they are almost impossible to find under ordinary circumstances unless a development project causes them to be exposed, such as occurred at the Windover site in Florida (Doran, 2002).

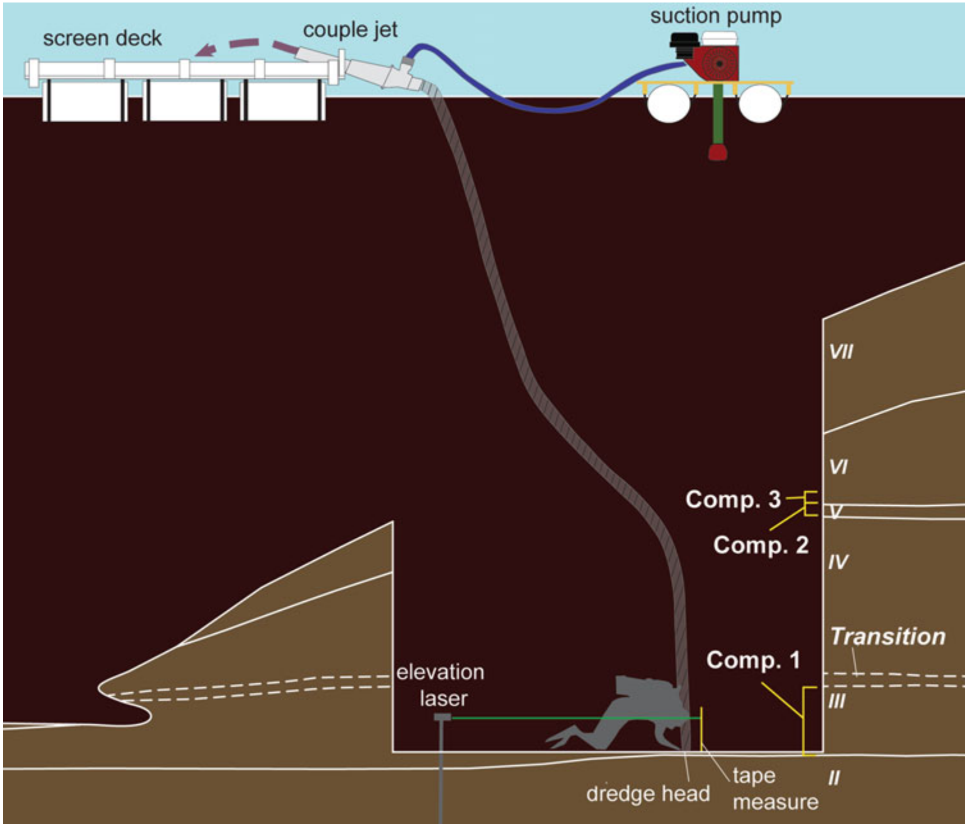
When looking for submerged sites, archaeologists often employ sonar surveys to locate areas of interest and gain an understanding of bottom topography. Everything from fishfinders to multibeam sonar systems has been utilized with some success to give the archaeologist a view of the bottom in two or three dimensions, while subbottom profilers give a profile view of the sediments directly below the machine. All of these types of remote sensing use sound waves of specific frequencies emitted at regular intervals. The machine emits the sounds and then "listens" for them to return after they bounce off a barrier or reflector of some kind. It keeps track of the travel time and performs complicated math to generate an "image" of the bottom that shows how far the wave traveled and how strongly it was reflected. See Chapter 13 of Bowens and Nautical Archaeology Society (2009) for an excellent summary of the main geophysical techniques utilized for site prospection.

When looking for shipwrecks or sites containing ferrous metals and built formal structures, side scanning sonar and magnetometers are the main survey equipment employed. Sonar systems do not usually have the resolution to see individual prehistoric artifacts or features (though see O'Shea et al., 2013). When looking for sites that predate the use of metals or are not associated with structures, archaeologists commonly look for landforms that would have attracted people, such as flat terraces adjacent to drowned streams or the edges of past waterholes. As buried sites are likely to be best preserved, they look at these localities more intensely for buried land surfaces. Thus, one must have some understanding of what the entire sediment column looked like. When feasible, subbottom profilers are used to give a sonar image of this. Many fishfinders now also have the ability to look through the top few meters of sediment, so they can be used as an inexpensive subbottom viewer to narrow down areas of interest.

Once target areas are defined, archaeologists next investigate them by a variety of more intensive means. At this point, a landform of interest has been defined, but no artifacts have been discovered, so it is not yet a definitive archaeological site. The archaeologist may then conduct visual surveys with SCUBA divers or underwater vehicles with cameras, swimming over the area looking for items of interest. If materials are likely to be buried, the archaeologists may use coring devices of various types. For instance, hand coring, vibrocoring, and Livingstone coring have been used in various seasons in Florida for soil prospection (Halligan, 2012). If logistics allow, test pits may be excavated with a dredge as well. During this phase, the researcher is looking for artifacts and/or incontrovertible evidence for submerged and preserved landforms, such as preserved buried soils in the cores or exposures of some cultural evidence. Soils form from the weathering of sediments in terrestrial contexts. Therefore, buried and inundated soils were surely exposed at some time in the past, and they could have been walked or lived upon by humans; they would therefore be worth further examination. Archaeologists will also look for places such as infilled sinkholes or ponds, places with exposed stone for flintknapping, and evidence of old shorelines, such as wave-cut notches, as these are all locations with resources that would have been attractive to people.

Underwater excavation is extremely expensive in comparison with terrestrial research (at least three to four times more expensive per day of research). Therefore, most underwater research is focused either entirely on survey and marking of areas of high potential or it is focused on excavation. If the latter, archaeologists will target only a few places with the highest probability of containing sites, which, in practice, usually means areas where erosion has exposed artifacts, allowing the researcher to spend less time on survey and more on excavation. Often, these sites have been revealed to the excavator by helpful local avocational archaeologists. This surface exposure, however, means that site context needs to be carefully examined, and artifacts must be discovered in situ in as yet undisturbed portions of the site in order to make any meaningful interpretations of human behavior in the past. Excavations on land and underwater must be carefully controlled so that artifact provenience can be carefully recorded.

The Page-Ladson site in Florida is a submerged sinkhole in the Aucilla River that contains some of the earliest archaeological material in North America. Research at this site was accomplished by excavating within 1x1 m grids that were laid in by tape and compasses from a datum placed underwater via Total Station. This is very similar to gridding a site on land. To control for elevations, archaeologists used a laser pointer specifically designed for underwater use that was mounted onto a level pole (Figure 1). The elevation of these poles was set from the datum point, and the laser was then an arbitrary line at a known height that would shoot across the unit, allowing excavators to take measurements below this line. Excavations were conducted by trowel to remove the sediments, with the backdirt sucked up to screens at the surface using a water dredge. Archaeologists on the surface maintained the air supply for divers and screened the sediments through nested 1/4″ and 1/16″ mesh in order to find even tiny artifacts and bones. Using this method, very accurate X, Y, and Z coordinates could be obtained for artifacts, sediment changes, and faunal remains 11 m below the river surface in water so tannin-stained that one could see only 1–2 m away even with a very bright light. Excavating with trowels and by hand allowed the archaeologists to tell instantly when digging was encountering a new stratum, and therefore, contextual associations could be recorded precisely.



Inundated Freshwater Settings, Figure 1 Generalized schematic of excavations at the Page-Ladson site, Florida, showing the excavation setup, the major stratigraphic units (in Roman numerals), and the three major cultural components found underwater (comp 1, comp 2, and comp 3).

Precise excavation is critical because artifact context is especially important for explicating site formation processes at underwater sites. The complicated logistics of working at these sites mean that only relatively small areas can be excavated in a field season, reducing the potential for finding cultural material in any given year's campaign; therefore, each artifact, feature, or ecofact is especially precious. Further, because few scientists have the training to visit the sites in person to draw their own conclusions about site formation, it is important to record the sites as thoroughly as possible. Finally, underwater sites often are more dynamic than their terrestrial counterparts, with excavation units filling in rapidly with leaves, sand, or other sediment, so dredging equipment is necessary, even just to see the site in many cases.

In the case of Page-Ladson, the disadvantage of dynamic change was mitigated by collecting numerous sediment samples for later lab analyses. To cross-check underwater interpretations of the stratigraphy, cores were collected using both vibrocoring equipment and a Livingstone-Bolivia corer, which were scanned for magnetic susceptibility and gamma density, photographed and described, and compared to the underwater unit descriptions. Paleoenvironmental samples were also extracted and analyzed for pollen, diatoms, phytoliths, and ancient DNA. The excellent preservation of the paleobotanicals represented one of the best sources of information, making this underwater site so significant to excavate even given its logistical difficulties. Inundated freshwater sites lack the salts that destroy organic remains in saline environments, so when the submerged burial environment is anaerobic, preservation can be remarkable. For example, 14,500-year-old grape skins were regularly noted in the sediments in the deepest levels of the site. Publication of these results is forthcoming.

Conservation and the benefits of excavating inundated terrestrial sites

Although underwater research can be costly, logistically intensive, and difficult, inundated freshwater sites can provide extremely important insights about past people because of the excellent preservation. For instance, at the Windover site (Doran, 2002), preservation of human burials was so good that brain tissue had survived for thousands of years in the underwater environment. The remains from this site helped to answer many questions about diet, mortality, and health in the early Holocene. The clothing and grave goods helped us understand how these early Americans crafted their material culture and presented themselves to others and gave some hints into their world view. Perhaps most importantly, archaeologists were forced to reconsider their own views about these early people due in large measure to the complementary artifactual assemblage encountered underwater. From more than 150 burials, there were fewer than 50 stone tools recovered. This is an especially significant reversal of expectation because stone artifacts are often the only material culture recovered from terrestrial sites of this age. The Windover site has reminded archaeologists about how little perishable material preserves on most terrestrial sites, and they have been forced to reassess the importance of stone tool technology to these forager societies because of what was *not* buried with the people discovered at Windover.

Inundated sites can reshape archaeological research based on the likelihood of finding a high degree of preservation, but they thus impose a higher level of responsibility. The rare gift of excellent preservation demands a more rigorous and costly commitment to logistics, time, and conservation for all the well-preserved organic materials. They afford extremely valuable insights about past people and past environments but only if properly conserved and curated. Thus, it is especially important to consider these factors, preferably in consultation with a trained conservator prior to data collection, although there are some useful references available for beginners (Pearson, 1987; Hamilton, 1999; Smith, 2003). As soon as organic materials are removed from the environment that has preserved them for so long, they will begin to degrade rapidly, and the potential information gained from them disappears. Thus, the decision to excavate these sites at all should be made with care and consideration for the cost of excavation and long-term conservation and curation.

Summary

In recent years, it has become increasingly apparent that many archaeological sites in freshwater settings have survived the inundation process and that these sites can be found and excavated with high levels of precision in some cases. Such freshwater sites often reveal extraordinary organic preservation, which allows for the recovery of artifact and ecofact types that are rarely found at coeval terrestrial sites, including DNA, microfossils, macrofossils, and organic tools. Recovery of these materials requires careful excavation, and conservation is a necessary part of the entire process if the delicate items are to survive for analyses. Discovery, excavation, conservation, and analysis of underwater sites in general are usually much more expensive and complex than their terrestrial counterparts, but the wealth of information recoverable from inundated freshwater sites can provide paradigm-changing insights about material culture and human behavior.

Bibliography

Balsillie, J. H., and Donoghue, J. F., 2004. *High Resolution Sea-Level History for the Gulf of Mexico Since the Last Glacial Maximum*. Tallahassee, FL: Florida Geological Survey. Report of Investigations, 103.

Balsillie, J. H., Means, G. H., and Dunbar, J. S., 2006. The Ryan/Harley site: sedimentology of an inundated Paleoindian site in north Florida. *Geoarchaeology*, **21**(4), 363–391.

Blum, M. D., and Törnqvist, T. E., 2000. Fluvial responses to climate and sea-level change: a review and look forward. *Sedimentology*, **47**(1), Suppl. 2–48.

Bowens, A., and Nautical Archaeology Society, 2009. *Underwater Archaeology: The NAS Guide to Principles and Practice*, 2nd edn. Portsmouth, UK/Malden, MA: Nautical Archaeology Society/Blackwell Publishers.

Chatters, J. C., Kennett, D. J., Asmerom, Y., Kemp, B. M., Polyak, V., Blank, A. N., Beddows, P. A., Reinhardt, E., Arroyo-Cabrales, J., Bolnick, D. A., Malhi, R. S., Culleton, B. J., Erreguerena Luna, P., Rissolo, D., Morell-Hart, S., and Stafford, T. W., Jr., 2014. Late Pleistocene human skeleton and mtDNA link Paleoamericans and modern Native Americans. *Science*, **344**(6185), 750–754.

Crisman, K. J., 2014a. *Coffins of the Brave: Lake Shipwrecks of the War of 1812*. College Station, TX: Texas A&M University Press.

Crisman, K. J., 2014b. The Western River steamboat *Heroine*, 1832–1838, Oklahoma, USA: construction. *International Journal of Nautical Archaeology*, **43**(1), 128–150.

Doran, G. H., 2002. *Windover: Multidisciplinary Investigations of an Early Archaic Florida Cemetery*. Gainesville, FL: University Press of Florida.

Dunbar, J. S., 2012. *The Search for Paleoindian Contexts in Florida and the Adjacent Southeast*. Ph.D. Dissertation, Department of Anthropology, Florida State University.

Graf, W. L., 2005. Geomorphology and American dams: the scientific, social, and economic context. *Geomorphology*, **71**(1–2), 3–26.

Halligan, J., 2012. *Geoarchaeological Investigations into Paleoindian Adaptations on the Aucilla River, Northwest Florida*. Ph.D. Dissertation, Department of Anthropology, Texas A&M University.

Hamilton, D. L., 1999. *Methods of Conserving Archaeological Material from Underwater Sites, Revision 1, Conservation Files: ANTH 605, Conservation of Cultural Resources I.* http://nautarch.tamu.edu/CRL/conservationmanual/ConservationManual.pdf, Nautical Archaeology Program, Department of Anthropology, Texas A&M University.

Harris, M. S., Sautter, L. R., Johnson, K. L., Luciano, K. E., Sedberry, G. R., Wright, E. E., and Siuda, A. N. S., 2013. Continental shelf landscapes of the southeastern United States since the last interglacial. *Geomorphology*, **203**, 6–24.

Hemmings, C. A., 1999. *The Paleoindian and Early Archaic Tools of Sloth Hole (8JE121): An Inundated Site in the Lower Aucilla River, Jefferson County, Florida*. M.A. thesis, Department of Anthropology, University of Florida, Gainesville.

Hicks, B. A., 2004. *Marmes Rockshelter: A Final Report on 11,000 Years of Cultural Use*. Pullman: Washington State University Press.

Hooge, J., 2013. *Underwater Geoarchaeology at Spring Lake, San Marcos, Texas*. Master's thesis, Department of Anthropology, Texas State University, San Marcos.

Leigh, D. S., 2008. Late Quaternary climates and river channels of the Atlantic coastal plain, southeastern USA. *Geomorphology*, **101**(1–2), 90–108.

Leshikar-Denton, M. E., and Luna Erreguerena, P., 2008. *Underwater and Maritime Archaeology in Latin American and the Caribbean*. Walnut Creek, CA: Left Coast Press.

Mazurkevich, A., and Dolbunova, E., 2011. Underwater investigation in northwest Russia: lacustrine archaeology of Neolithic pile dwellings. In Benjamin, J., Bonsall, C., Pickard, C., and Fischer, A. (eds.), *Submerged Prehistory*. Oxford: Oxbow Books, pp. 158–172.
Milliken, K. T., Anderson, J. B., and Rodriguez, A. B., 2008. A new composite Holocene sea-level curve for the northern Gulf of Mexico. In Anderson, J. B., and Rodriguez, A. B. (eds.), *Response of Upper Gulf Coast Estuaries to Holocene Climate Change and Sea-Level Rise*. Boulder, CO: Geological Society of America, pp. 1–11. GSA special paper, 443.
O'Shea, J., Lemke, A. K., and Reynolds, R. G., 2013. "Nobody Knows the Way of the Caribou": Rangifer hunting at 45° North latitude. *Quaternary International*, **297**, 36–44.
Pearson, C., 1987. *Conservation of Marine Archaeological Objects*. London: Butterworths.
Peltier, W. R., and Fairbanks, R. G., 2006. Global glacial ice volume and Last Glacial Maximum duration from an extended Barbados sea level record. *Quaternary Science Reviews*, **25**(23–24), 3322–3337.
Schumm, S. A., 1973. Geomorphic thresholds and complex response of drainage systems. In Morisawa, M. (ed.), *Fluvial Geomorphology: A Proceedings Volume of the Fourth Annual Geomorphology Symposia Series held at Binghamton, New York, September 27–28, 1973*. Binghamton, NY: New York State University Publications in Geomorphology. Binghamton Symposia in Geomorphology, Vol. 4, pp. 299–310.
Smith, C. W., 2003. *Archaeological Conservation Using Polymers: Practical Applications for Organic Artifact Stabilization*. College Station, TX: Texas A & M University Press.
Sonnenburg, E. P., Boyce, J. I., and Reinhardt, E. G., 2011. Quartz flakes in lakes: microdebitage evidence for submerged Great Lakes prehistoric (Late Paleoindian-Early Archaic) tool-making sites. *Geology*, **39**(7), 631–634.
Talbot, M. R., 2005. Sedimentary environments: lake processes and deposits. In Selley, R. C., Cocks, L. R. M., and Plimer, I. R. (eds.), *Encyclopedia of Geology*. Oxford: Elsevier, pp. 550–561.
Webb, S. D. (ed.), 2006. *First Floridians and Last Mastodons: The Page-Ladson Site in the Aucilla River*. Dordrecht, The Netherlands: Springer.
Wheeler, R. J., Miller, J. J., McGee, R. M., Ruhl, D., Swan, B., and Memory, M., 2003. Archaic period canoes from Newnans Lake, Florida. *American Antiquity*, **68**(3), 533–551.
Wolman, M. G., and Miller, J. P., 1960. Magnitude and frequency of forces in geomorphic processes. *Journal of Geology*, **68**(1), 54–74.

Cross-references

Alluvial Settings
Archaeological Stratigraphy
Artifact Conservation
Coastal Settings
Colluvial Settings
Geomorphology
Magnetometry for Archaeology
Organic Residues
Paleoenvironmental Reconstruction
Paleoshores (Lakes and Sea)
Paludal Settings (Wetland Archaeology)
Pre-Clovis Geoarchaeology
Radiocarbon Dating
Shipwreck Geoarchaeology
Soils
Submerged Continental Shelf Prehistory

ISERNIA

Francesco G. Fedele
Formerly University of Naples 'Federico II', Naples, Torino, Italy

Definition

Isernia is a Lower Paleolithic open-air site in Molise, central Italy, with geographic coordinates of 41°35′27″ N, 14°14′29″ E. It lies at 455–460 m asl.

The archaeological site of La Pineta at Isernia, accidentally discovered during roadwork in 1978, is located on the western border of the Middle Pleistocene Isernia Basin, in the lower range of the Apennines. A stratified fluviolacustrine sequence including four cultural layers is documented, with several artifact- and bone-bearing levels interpreted as "living floors" (Fr. *sols d'habitat*) produced by repeated camping of hominins (Peretto et al., 1983; Peretto and Minelli, 2006). The closeness to a regularly flooding stream and the occurrence of volcanic events contributed to good preservation of the site, which was covered by silt and clay of riverine origin alternating with volcanic tuffs.

Showing a normal magnetic polarity, the whole sequence was deposited during the Brunhes Chron, i.e., in the Middle Pleistocene. Earlier age evaluations were contradictory, but the latest magnetostratigraphic and $^{39}Ar/^{40}Ar$ determinations have allowed the dating of the main archaeological level (t3a, a debris flow deposit) to 606 ± 2 ka (Coltorti et al., 2005), with ESR ages on bovid enamel in acceptable agreement (560 ± 84 ka; Bahain et al., 2007). Lithic artifacts include heavy-duty implements from locally available stones, mostly choppers, and flint and limestone flake tools (Peretto, 1994). Animal remains of cultural introduction are dominated by elephants (*Palaeoloxodon antiquus*), rhinoceri (*Stephanorhinus hundsheimensis*), and hippopotami (*Hippopotamus* cf. *antiquus*). Less frequent species include bears, wild boars, and Megaceros deer; occasional lion (*Panthera leo*) remains are among the earliest in Europe.

The sedimentary, palynological, and paleontological evidence suggests a persistent environmental mosaic in which large prairies alternated with marshes and low-mountain forests. In 2014, a deciduous hominin incisor attributed to *Homo heidelbergensis* was found on the surface of unit t3a. Interdisciplinary-oriented excavations are continuing, and an onsite museum has been created to allow the public a glimpse of Paleolithic archaeology and geoarchaeology in action.

Bibliography

Bahain, J.-J., Falguères, C., Voinchet, P., Duval, M., Dolo, J.-M., Despriée, J., Garcia, T., and Tissoux, H., 2007. Electron spin resonance (ESR) dating of some European late lower Pleistocene sites. *Quaternaire*, **18**(2), 175–185.

Coltorti, M., Feraud, G., Marzoli, A., Peretto, C., Ton-That, T., Voinchet, P., Bahain, J.-J., Minelli, A., and Thun-Hohenstein, U., 2005. New ^{40}Ar/^{39}Ar, stratigraphic and palaeoclimatic data on the Isernia La Pineta Lower Palaeolithic site, Molise, Italy. *Quaternary International*, **131**(1), 11–22.
Peretto, C., 1994. *Le Industrie Litiche del Giacimento Paleolitico di Isernia La Pineta. 1. La Tipologia, le Tracce di Utilizzazione, la Sperimentazione*. Isernia: Cosmo Iannone Editore.
Peretto, C., and Minelli, A. (eds.), 2006. *Preistoria in Molise. Gli Insediamenti del Territorio di Isernia*. Rome: Aracne Editrice.
Peretto, C., Terzani, C., and Cremaschi, M. (eds.), 1983. *Isernia la Pineta. Un Accampamento Più Antico di 700 000 Anni*. Bologna: Calderini.

ISOCHRON DATING

Jan D. Kramers
Department of Geology, University of Johannesburg, Auckland Park Kingsway Campus, Auckland Park, Johannesburg, South Africa

Definition

Isochron A term derived from Greek meaning "same time" that refers to a straight line given by the regression calculated for points plotted in X–Y space that represent isotope abundance ratios across a set of samples (minerals or rocks) of the same age; it is a graphical tool employed in radiometric age determination.

The isochron dating method is applicable to all radioactive decay systems used in geochronology. In archaeology and paleoanthropology, the uranium-lead variant has been applied since 2006 (Walker et al., 2006) for dating speleothems (stalagmites and flowstones) older than the ca. 500,000 year age limit for U-series dating.

Essentially, the isochron diagram describes isotopic changes since the formation of a rock. At crystallization (whether from a magma or from drip water in a cave), the parent radioisotope (P) and its stable daughter product (D) within the newly formed rock or mineral would present an initial ratio of D_0/P_0 and register an age of zero based on the absence of accumulated daughter product. Over time, decay of the parent would lead to a decrease in its quantity and an equal increase in the stable daughter isotope. Using a different stable isotope of the daughter (S) as a reference, and plotting the ratios of D/S against P/S for several samples collected from the same rock layer (and representing the same age of formation), the plotted points would form a straight line, and the slope of the regression should increase with the age of the sample. This is possible only if the production of new daughter product D occurred within a closed system with no outside disturbances and all samples analyzed possessed the same initial D_0/S_0 ratio.

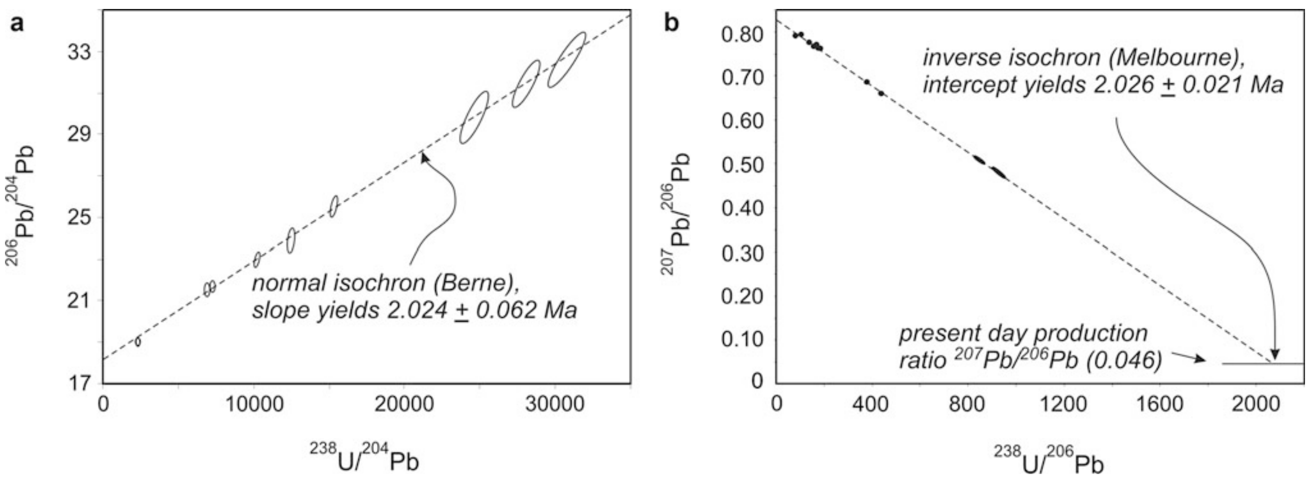
In the most commonly used (normal) isochron diagram applicable to speleothems, the abundance of a long-lived radioactive isotope P (e.g., ^{238}U) and its stable daughter isotope D (e.g., ^{206}Pb) are plotted. Both abundances are given relative to the same stable reference isotope of the daughter element S (e.g., ^{204}Pb). Simply stated, the isotope ratios ^{238}U/^{204}Pb (i.e., P/S) and ^{206}Pb/^{204}Pb (i.e., D/S) are determined for several samples and plotted on an isochron graph (Figure 1a). If P/S is displayed on the abscissa (x-axis) and D/S on the ordinate (y-axis), then the positive slope of the isochron (D/P) yields the age of the samples: Age = $\ln(D/P + 1)/\lambda$. Here, λ is the decay constant of ^{238}U, which is 1.55125×10^{-10} year^{-1}.

Another value that can be of importance for geochemical interpretation is the initial isotope ratio. This is the D/S ratio (e.g., ^{206}Pb/^{204}Pb) that the samples defining an isochron had at the time they were formed. It is indicated by the intersection of the normal isochron with the y-axis.

Somewhat analogous to its usage in ^{40}Ar/^{39}Ar dating, an inverse isochron is frequently applied in U-Pb dating of Neogene samples (dating between 23 and 3 Ma ago). This can be seen in the regression line with negative slope for a plot of ^{207}Pb/^{206}Pb versus ^{238}U/^{206}Pb (Figure 1b). It is in fact a mixing line between the initial ^{207}Pb/^{206}Pb ratio of the samples indicated at the Y-intercept and pure radiogenic ^{206}Pb (derived from the decay of ^{238}U) represented by the intersection of the isochron with the horizontal line giving the present-day ^{207}Pb/^{206}Pb production ratio (0.046) from the decay of ^{235}U and ^{238}U, respectively. The age is derived as above from the D/P ratio: 1/(^{238}U/^{206}Pb) at this intersection. The inverse isochron method plots the ratio of parent/daughter along the x-axis unlike the normal method, which separates parent and daughter on the x-axis and y-axis; it also does not require measurement of the minor stable isotope ^{204}Pb and is therefore more precise (compare Figure 1a, b). It does, however, rely on the assumption that the initial ^{207}Pb/^{206}Pb ratio was uniform among the samples.

U-Pb isochrons yield the correct ages for the samples only if the intermediate nuclides in the ^{238}U decay chain existed in secular equilibrium at the time the dated minerals or rocks (e.g., speleothems) were formed. ^{230}Th is normally absent in speleothems when they form, necessitating an upward correction of the apparent isochron age by about 80,000 years. On the other hand, ^{234}U is frequently present in excess, and this requires a downward correction which can be as great as 700,000 years. In samples younger than about three million years, a residual excess of ^{234}U can in many cases still be detected, which allows the correction to be made (Walker et al., 2006). In older samples, ^{234}U and ^{238}U are, within the uncertainty limits of measurements, in secular equilibrium. It must then be accepted that the true age may be up to 700,000 years younger than the value yielded by an isochron.

For example, following the discovery of fossils of the new hominin species *Australopithecus sediba* in 2008 at the Malapa site, Gauteng, South Africa (Berger et al., 2010), a flowstone horizon underlying the fossiliferous clastic cave sediments was independently dated by university laboratories in Berne, Switzerland, and Melbourne,



Isochron Dating, Figure 1 Normal (**a**) and inverse (**b**) uranium-lead isochrons obtained on flowstone layers with ca. 1 ppm U at the Malapa fossil site, Gauteng, South Africa. Age results quoted, and error ellipses in (**a**) are at the 95 % confidence level. Error ellipses in (**b**) are mostly smaller than symbols (Modified from Dirks et al., 2010).

Australia, using the normal and inverse isochron methods, respectively (Dirks et al., 2010; Figure 1). Later, the combination of these results with those from a flowstone overlying the fossils as well as paleomagnetic data yielded a precise age of 1.977 ± 0.002 million years (Ma) for the fossils (Pickering et al., 2011).

Bibliography

Berger, L. R., de Ruiter, D. J., Churchill, S. E., Schmid, P., Carlson, K. J., Dirks, P. H. G. M., and Kibii, J. M., 2010. *Australopithecus sediba*: a new species of homo-like australopith from South Africa. *Science*, **328**(5975), 195–204.

Dirks, P. H. G. M., Kibii, J. M., Kuhn, B. F., Steininger, C., Churchill, S. E., Kramers, J. D., Pickering, R., Farber, D. L., Mériaux, A.-S., Herries, A. I. R., King, G. C. P., and Berger, L. R., 2010. Geological setting and age of *Australopithecus sediba* from Southern Africa. *Science*, **328**(5975), 205–208.

Pickering, R., Dirks, P. H. G. M., Jinnah, Z., de Ruiter, D. J., Churchill, S. E., Herries, A. I. R., Woodhead, J. D., Hellstrom, J. C., and Berger, L. R., 2011. *Australopithecus sediba* at 1.977 Ma and implications for the origins of the genus Homo. *Science*, **333**(6048), 1421–1423.

Walker, J., Cliff, R. A., and Latham, A. G., 2006. U–Pb isotopic age of the StW 573 hominid from Sterkfontein, South Africa. *Science*, **314**(5805), 1592–1594.

Cross-references

$^{40}Ar/^{39}Ar$ and K–Ar Geochronology
Paleomagnetism
Speleothems
U-Series Dating

J

JAVA (INDONESIA)

O. Frank Huffman
Department of Anthropology, University of Texas at Austin, Bastrop, TX, USA

Java is a Southeast Asian island with special geoarchaeological significance. Since 1890, geological studies in its eastern part have supported the discovery and interpretation of >100 skeletal fossils of *Homo erectus*, an extinct human ancestor (Theunissen et al., 1990; Zaim, 2010). There have been no confirmed finds of Homo erectus in other areas of Southeast Asia or Australia.

When Eugene Dubois chose Java in 1890 to search for fossil connections between *Homo sapiens* and apes, he focused his attention on cave deposits and volcanic-rich sedimentary rocks that were known to contain mammalian bones. He soon found what he called the skeletal "missing link" – *Homo erectus* (initially named *Pithecanthropus erectus*) – in excavations at Trinil along the Solo River (Shipman, 2001). The bone bed contain the Homo erectus fossil was a conglomeratic sandstone lens, <1 m thick, that was part of the local bedrock. The lens produced many thousands of teeth and strongly fossilized bones representing deer, cattle, *Stegodon* (a large late Cenozoic to Quaternary proboscidean), and other terrestrial animals, mixed with the remains of hippopotamus, crocodile, freshwater mollusks, and trees. Evidence of shellfish consumption and shell engraving has recently been found (Joordens et al., 2015).

In 1931–1933, geologists excavated 12 partial *Homo erectus* calvaria (skullcaps including parts of the frontal, parietal, and occipital bones) and two long bones from another thin bone bed (Huffman et al., 2010). The new discoveries came from river terrace deposits at Ngandong, 10 km from Trinil. Several years later, the fossilized braincase of an infant was unearthed from fossil-rich gravelly sandstone, ~3.3 m thick, deposited in a channel of an ancient marine delta, 125 km east of Trinil. Like earlier finds, this specimen was embedded in sediment eroded from episodically active stratovolcanoes, which are numerous in Java. Over subsequent decades, *Homo erectus* discoveries have been most numerous 60 km west of Trinil at Sangiran Dome, where the fossils were contained within fluvial and lacustrine deposits together with a few artifacts and cut-marked bones. No *Homo erectus* fossils are known from the many karstic caves of eastern Java, but Song Terus cavern, 100 km south of Trinil, contains artifacts attributable to the species (Sémah et al., 2002).

Eastern Java was favorable for *Homo erectus* occupation and fossilization during roughly a million years of the Pleistocene. Dietary resources of aquatic, forest, and large mammal origin present along rivers draining stratovolcanoes evidently sustained recurring or continuous *Homo erectus* inhabitation, while rapid volcaniclastic deposition, sometimes following debris flows in the highlands, served to preserve skeletal remains (Huffman et al., 2012). Additional geoarchaeological research on Java *Homo erectus* is needed, especially on chronometric dating of occupations and determining coeval paleoenvironmental conditions.

Bibliography

Huffman, O. F., de Vos, J., Berkhout, A. W., and Aziz, F., 2010. Provenience reassessment of the 1931–1933 Ngandong *Homo erectus* (Java), confirmation of the bone-bed origin reported by the discoverers. *PaleoAnthropology*, **2010**, 1–60.

Huffman, O. F., Voight, B., de Vos, J., Johnson, J. P., Balzeau, A., and Berkhout, A. W. 2012. Volcanic mountains, river valleys and seacoasts – the paleoenvironment of *Homo erectus* in eastern Java (Indonesia). *Quaternary International*, **279**–**280**, 210.

A.S. Gilbert (ed.), *Encyclopedia of Geoarchaeology*, DOI 10.1007/978-1-4020-4409-0,

In Schlüchter, C., and Nietlispach, J. (eds.), Special Issue, XVIII INQUA Congress, 21–27 July, 2011, Bern.

Joordens, J. C. A., d'Errico, F., Wesselingh, F. P., Munro, S., de Vos, J., et al. 2015. Homo erectus at Trinil on Java used shells for tool production and engraving. *Nature*, **518**, 228–231.

Sémah, F., Sémah, A.-M., and Simanjuntak, T., 2002. More than a million years of human occupation in insular southeast Asia: the early archaeology of eastern and central Java. In Mercader, J. (ed.), *Under the Canopy: The Archaeology of Tropical Rainforests*. New Brunswick: Rutgers University Press, pp. 161–190.

Shipman, P., 2001. *The Man Who Found the Missing Link: Eugène Dubois and His Lifelong Quest to Prove Darwin Right*. New York: Simon & Schuster.

Theunissen, B., de Vos, J., Sondar, P. Y., and Aziz, F., 1990. The establishment of a chronological framework for the hominid-bearing deposits of Java; a historical survey. In Laporte, L. F. (ed.), *Establishment of a Geologic Framework for Paleoanthropology.* Boulder, CO: Geological Society of America. Geological Society of America Special Paper 242, pp. 39–54.

Zaim, Y., 2010. Geological evidence for the earliest appearance of hominins in Indonesia. In Feagle, J. G., Shea, J. J., Grine, F. E., Baden, A. L., and Leakey, R. E. (eds.), *Out of Africa I, The First Hominin Colonization of Eurasia*. Dordrecht: Springer, pp. 97–110.

K

KEBARA CAVE

Paul Goldberg
Department of Archaeology, Emeritus at Boston University, Boston, MA, USA

The site of Kebara, located along the western side of Mt. Carmel, ~30 km south of Haifa, Israel, is formed in a Cretaceous limestone reef complex at an elevation of ca. 60 m asl (Figure 1) (Bar-Yosef et al., 1992, 1996; Bar-Yosef and Meignen, 2007). Initial excavations by Turville-Petre (1932) exposed deposits with Natufian, Kebaran, and Upper Paleolithic implements; later excavations explored Upper and Middle Paleolithic deposits (Schick and Stekelis, 1977).

The sediments are geogenic and anthropogenic, with the latter especially apparent in the Middle Paleolithic (Goldberg et al., 2007). Geological processes include the following:

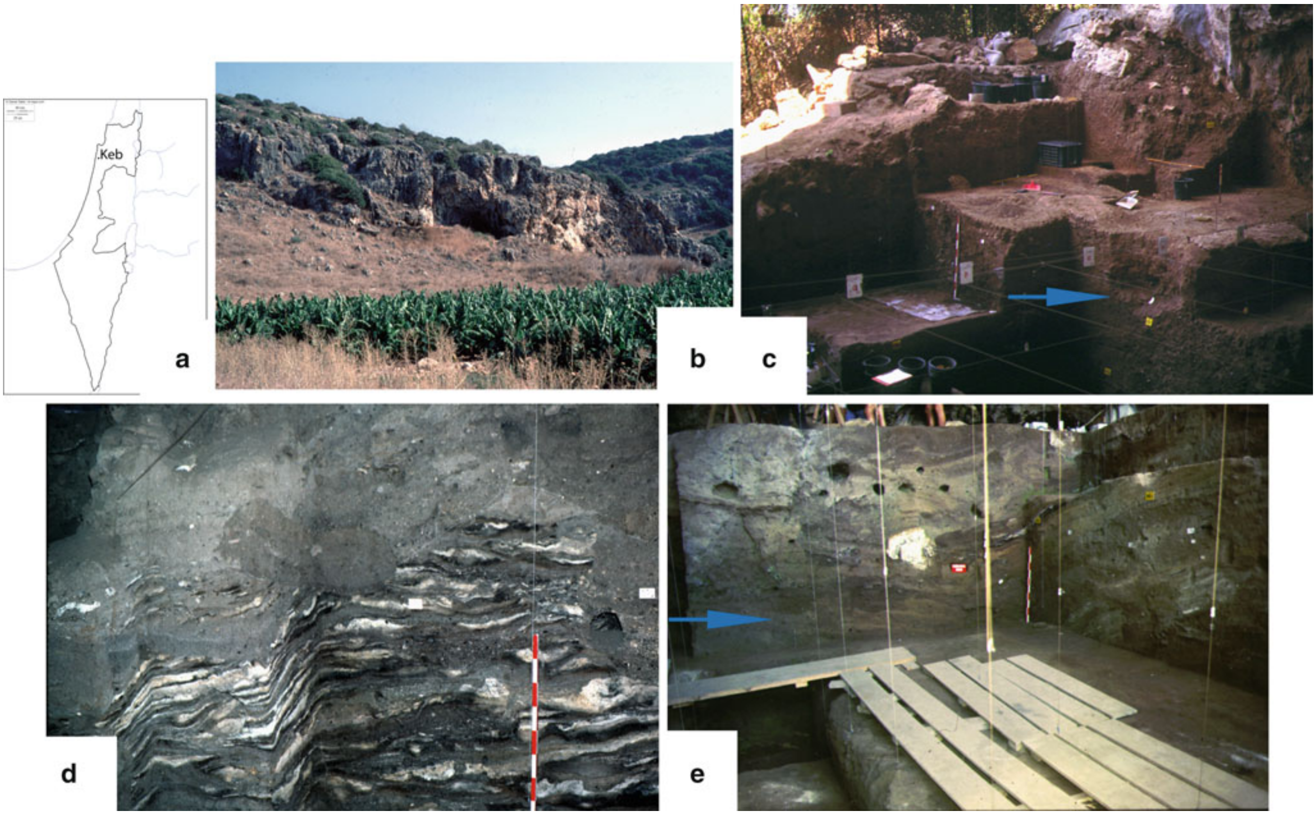
(a) Deposition of basal sands is associated with preoccupation phreatic water flow.
(b) Red colluvial silty clays occurring at the entrance to the cave are terra rossa soils reworked from Mt. Carmel above the cave (some were also washed in through a chimney at the rear of the cave).
(c) The deposits of (b) and older ones at the entrance were also reworked by sheet wash, particularly during the Upper Paleolithic under wetter conditions.
(d) Collapse of meter-sized limestone blocks from the cliff above the cave entrance during the Upper Paleolithic.
(e) Weak aeolian inputs of silt and sand.

Anthropogenic processes are signified by numerous lenticular and tabular combustion features and their remains (e.g., charcoal and ashes) (Meignen et al., 2007). These features prevail in the Middle Paleolithic layers but are rare in the Upper Paleolithic and later sediments. Micromorphological analysis shows that the Middle Paleolithic (Mousterian) features also include ash dumps and hearth cleanouts as well as in situ burning events.

Postdepositional effects include phosphate diagenesis (Schiegl et al., 1996), which results in extensive dissolution of bones. Calcite precipitation occurs in areas adjacent to the bedrock walls. Physical modifications include localized slumping and faulting; a major slumping event took place at the end of the Middle Paleolithic, producing >2 m of relief from front to back. Bioturbation (mammal and insect) is local but widespread.

Thermoluminescence (TL) dates on burnt Mousterian flints range between 48000 and 60000 BP (Valladas et al., 1987). Several radiocarbon dates place the transition from Middle to Upper Paleolithic between 49/48 and 47/46 k radiocarbon calibrated years before present (years cal BP) (Bar-Yosef et al., 1996; Rebollo et al., 2011).

A.S. Gilbert (ed.), *Encyclopedia of Geoarchaeology*, DOI 10.1007/978-1-4020-4409-0,



Kebara Cave, Figure 1 Kebara Cave, Mount Carmel, Israel. (**a**) Location of Kebara Cave in northern Israel. (**b**) View of the cave looking toward the east. The cave is developed in a Cretaceous limestone reef. (**c**) View of the entrance to the cave from the rear showing predominantly reworked terra rossa overlying grey, tilted, and phosphatized Middle Paleolithic deposits; *arrow* shows contact. (**d**) Middle Paleolithic deposits in the west face of the deposits showing numerous combustion features in the *lower* part. The *upper* part is compositionally similar but has been bioturbated and slumped; the elliptical feature in the *center* of the photo is an ancient animal burrow (possibly badger or porcupine). (**e**) View of the sediments at the rear of the cave. The *right side* of the photograph shows strata dipping toward the back of the cave, a result of subsidence into a subsurface depression during the end of the Middle Paleolithic. Consequently, most of the deposits on the *left* are Upper Paleolithic even though they are at comparable elevations to those in (**d**), which are exposed on the opposite side of the excavation unit. *Arrow* points to the approximate contact between the Middle and Upper Paleolithic deposits.

Bibliography

Bar-Yosef, O., and Meignen, L., 2007. *Kebara Cave, Mt. Carmel, Israel: The Middle and Upper Paleolithic Archaeology, Part 1*. Cambridge, MA: Peabody Museum of Archaeology and Ethnology, Harvard University. American School of Prehistoric Research Bulletin, Vol. 49.

Bar-Yosef, O., Vandermeersch, B., Arensburg, B., Belfer-Cohen, A., Goldberg, P., Laville, H., Meignen, L., Rak, Y., Speth, J. D., Tchernov, E., Tillier, A.-M., and Weiner, S., 1992. The excavations in Kebara Cave, Mt. Carmel. *Current Anthropology*, **33**(5), 497–550.

Bar-Yosef, O., Arnold, M., Mercier, N., Belfer-Cohen, A., Goldberg, P., Housley, R., Laville, H., Meignen, L., Vogel, J. C., and Vandermeersch, B., 1996. The dating of the Upper Paleolithic layers in Kebara Cave, Mt Carmel. *Journal of Archaeological Science*, **23**(2), 297–306.

Goldberg, P., Laville, H., Meignen, L., and Bar-Yosef, O., 2007. Stratigraphy and geoarchaeological history of Kebara Cave, Mount Carmel. In Bar-Yosef, O., and Meignen, L. (eds.), *Kebara Cave, Mt. Carmel, Israel: The Middle and Upper Paleolithic Archaeology, Part 1*. Cambridge, MA: Peabody Museum of Archaeology and Ethnology, Harvard University. American School of Prehistoric Research Bulletin, Vol. 49, pp. 49–89.

Meignen, L., Goldberg, P., and Bar-Yosef, O., 2007. The hearths at Kebara Cave and their role in site formation processes. In Bar-Yosef, O., and Meignen, L. (eds.), *Kebara Cave, Mt. Carmel, Israel: The Middle and Upper Paleolithic Archaeology, Part 1*. Cambridge, MA: Peabody Museum of Archaeology and Ethnology, Harvard University. American School of Prehistoric Research Bulletin, Vol. 49, pp. 91–122.

Rebollo, N. R., Weiner, S., Brock, F., Meignen, L., Goldberg, P., Belfer-Cohen, A., Bar-Yosef, O., and Boaretto, E., 2011. New radiocarbon dating of the transition from the Middle to the Upper Paleolithic in Kebara Cave, Israel. *Journal of Archaeological Science*, **38**(9), 2424–2433.

Schick, T., and Stekelis, M., 1977. Mousterian assemblages in Kebara Cave, Mount Carmel. *Eretz-Israel*, **13**, 97–149.

Schiegl, S., Goldberg, P., Bar-Yosef, O., and Weiner, S., 1996. Ash deposits in Hayonim and Kebara Caves, Israel: macroscopic, microscopic and mineralogical observations, and their archaeological implications. *Journal of Archaeological Science*, **23**(6), 763–781.
Turville-Petre, F., 1932. The excavations in the Mugharet et-Kebarah. *Journal of the Royal Anthropological Institute of Great Britain and Ireland*, **62**, 271–276.
Valladas, H., Joron, J. L., Valladas, G., Arensburg, B., Bar-Yosef, O., Belfer-Cohen, A., Goldberg, P., Laville, H., Meignen, L., Rak, Y., Tchernov, E., Tillier, A. M., and Vandermeersch, B., 1987. Thermoluminescence dates for the Neanderthal burial site at Kebara in Israel. *Nature*, **330**(6144), 159–160.

KENNEWICK MAN

Gary Huckleberry
Department of Geosciences, University of Arizona, Tucson, AZ, USA

Definition

Kennewick Man is a ∼9,200-year-old skeleton that became the focus of a legal battle over interpretation of US law regarding disposition of ancient human remains.

Human skeletal remains discovered in 1996 along the shore of Lake Wallula (Columbia River) in Kennewick, Washington, yielded a $\delta^{13}C$-corrected radiocarbon age of 8,410 ± 60 years BP, making it one of the oldest, well-preserved skeletons from the Pacific Northwest (Chatters, 2000). Preliminary analysis indicated that the skull morphology did not match modern Native Americans, generating considerable public and scientific debate. Several Northwestern Native American tribes requested that the skeletal remains be immediately repatriated, citing the 1990 Native American Graves Protection and Repatriation Act (NAGPRA). The federal government announced its intention to give the skeleton to representatives of local tribes for reburial, but a group of scientists filed suit (Bonnichsen et al. vs. US Government) and argued that the skeleton should be retained for scientific study.

In order to gain contextual information on the skeleton, a preliminary geological study of the discovery site was conducted in 1997 (Wakeley et al., 1998; Chatters, 2000). The shore of Lake Wallula exposes a Holocene alluvial terrace of the Columbia River. Contained within the alluvium was a volcanic ash layer identified as the 7,600-year-old Mazama tephra. A soil that had developed within the terrace beneath the Mazama tephra contained secondary carbonate nodules similar to those that were described as adhering to the skeleton. The preliminary interpretation was that the skeleton had eroded out of alluvial deposits located stratigraphically beneath the Mazama tephra, but that more detailed analysis of the site and skeleton were needed to test this hypothesis. The site was buried by the Army Corps of Engineers (ACE) in 1998 before the study could be completed.

In 1999, the US Department of the Interior (DOI) selected a team of scientists not included in the lawsuit to perform a series of tests to help determine the applicability of NAGPRA to Kennewick Man (www.nps.gov/archeology/kennewick/). Although the discovery site had been covered by the ACE, it was possible to analyze sediments adhering to the skeleton and compare them with stratigraphic information obtained during the site investigation. Granulometric, mineralogical, and chemical analyses were conducted on sediments that were removed from the exterior of several postcranial elements and that had been collected from the site during the initial investigation. In addition, micromorphological analysis was performed on an intact aggregate of sediment from within the skull. Results of this forensic geoarchaeological study reaffirmed that Kennewick Man originated from pre-Mazama alluvium and was quickly buried by ancient sediments after death (Huckleberry et al., 2003).

Further radiocarbon testing on bone confirmed that the skeleton was ∼9,200 years old. The case eventually went to trial, and a federal court decision was rendered in 2002 stating that cultural affiliation could not be determined for such an ancient skeleton and that plaintiff scientists could study the skeleton. Results of biometric, chronometric, isotopic, and taphonomic analyses conducted by plaintiff scientists and colleagues are detailed in Owsley and Jantz (2014). Meanwhile, Kennewick Man remains locked in a vault in the Burke Museum, University of Washington, Seattle. For different perspectives regarding Kennewick Man and NAGPRA, see Thomas (2000), Bruning (2006), Burke et al. (2008), and Weiss (2008); also see Friends of America's Past (www.friendsofpast.org).

Bibliography

Bruning, S. B., 2006. Complex legal legacies: the Native American Graves Protection and Repatriation Act, scientific study, and Kennewick Man. *American Antiquity*, **71**(3), 501–521.
Burke, H., Smith, C., Lippert, D., Watkins, J., and Zimmerman, L. (eds.), 2008. *Kennewick Man: Perspectives on the Ancient One*. Walnut Creek: Left Coast Press.
Chatters, J. C., 2000. The recovery and first analysis of an early Holocene human skeleton from Kennewick, Washington. *American Antiquity*, **65**(2), 291–316.
Huckleberry, G., Stein, J. K., and Goldberg, P., 2003. Determining the provenience of Kennewick Man skeletal remains through sedimentological analyses. *Journal of Archaeological Science*, **30**(6), 651–665.
Owsley, D. W., and Jantz, R. L. (eds.), 2014. *Kennewick Man: The Scientific Investigation of an Ancient American Skeleton*. College Station: Texas A&M University Press.
Thomas, D. H., 2000. *Skull Wars: Kennewick Man, Archaeology, and the Battle for Native American Identity*. New York: Basic Books.
Wakeley, L. D., Murphy, W. L., Dunbar, J. B., Warne, A. G., Briuer, F. L., and Nickens, P. R., 1998. *Geologic, Geoarchaeologic, and Historical Investigations of the Discovery Site of Ancient*

Remains in Columbia Park, Kennewick, Washington. Vicksburg: U.S. Army Corps of Engineers Waterways Experiment Station. Technical Report GL-98-13.

Weiss, E., 2008. *Reburying the Past: The Effects of Repatriation and Reburial on Scientific Inquiry*. New York: Nova Science Publishers.

Cross-references

Alluvial Settings
Forensic Geoarchaeology
Tephrochronology

KOSTENKI, RUSSIA

Vance T. Holliday[1] and John F. Hoffecker[2]
[1]Anthropology and Departments Geosciences, University of Arizona, Tucson, AZ, USA
[2]INSTAAR (Institute of Arctic and Alpine Research), University of Colorado, Boulder, CO, USA

The Kostenki-Borshchevo localities include 26 Upper Paleolithic open-air sites in well-stratified contexts along the Don River, ~40 km southwest of the Russian city of Voronezh on the East European Plain (Holliday et al., 2007). The well-expressed and relatively uniform stratigraphy among these sites has long been recognized by field investigators (e.g., Lazukov, 1957; Velichko, 1961; Grishchenko, 1976; Sinitsyn et al., 1997; Kholmovoi and Nesterova, 2001) and has been a primary means of correlating the many occupation sequences (e.g., Praslov and Rogachev, 1982). Prior to the development of numerical dating methods, stratigraphy was the only means of establishing the relative chronology (Rogachev, 1957).

Study of the Kostenki-Borshchevo sites had a significant impact on Paleolithic archaeology in Eastern Europe (Klein, 1969, 26–31; Hoffecker, 2002, 148–151). The initial discovery of stone artifacts and mammoth bones at Kostenki 1 in 1879 helped document the presence of Paleolithic people in Russia, and since that time, many prominent Soviet and Russian archaeologists have worked at these sites (Praslov, 1982). Much of the investigation prior to World War II was focused on the spectacular feature complex and associated remains in the uppermost layer at Kostenki 1 (Efimenko, 1958). The emphasis on broad horizontal excavations and mapping of former dwellings and other features (termed the "Kostenki School") promoted the analysis of Paleolithic social and economic patterns many years before this became a focus of research in Western Europe. After World War II, A. N. Rogachev and several geologist colleagues expanded the study of earlier Upper Paleolithic remains and their stratigraphic context (Lazukov, 1957; Rogachev, 1957), and in recent years, it has become clear that the primary importance of the Kostenki sites lies in their early Upper Paleolithic record, which contains evidence of Upper Paleolithic occupation of the East European Plain before 40,000 years ago (e.g., Anikovich et al., 2007).

Most of the Kostenki-Borshchevo sites are on the first and second terraces along the west bank of the Don River. Recent geoarchaeological research (e.g., Holliday et al., 2007) focused on the sites of Kostenki 1, 12, and 14, with more limited work at Kostenki 8, 11, 16, and 17, and Borshchevo 5. The strata are grouped into three units, described here from the bottom up. Unit 1, >50 cal ka, consists of coarse alluvium (representing upper terrace 2 deposits) and colluvium, overlain by fine-grained sediments. Unit 2 includes archaeological horizons sealed within two sets of thin lenses of silt, carbonate, chalk fragments, and organic-rich soils (termed *lower humic bed* and *upper humic bed*) dating 50–30 cal ka. Several horizons buried in the lower part of Unit 2 contain Upper Paleolithic assemblages. Separating the humic beds is a volcanic ash lens identified as the Campanian Ignimbrite Y5 tephra, dated elsewhere by Ar/Ar to ca. 40 cal ka (Pyle et al., 2006; Giaccio et al., 2008). The humic beds appear to result from the complex interplay of soil formation, spring deposition, slope action, and other processes. The springs and seeps, which are present in the area today, emanated from the bedrock valley wall. Their presence may account for the unusually high concentration of Upper Paleolithic sites in this part of the central East European Plain. Unit 3, <30 cal ka, contains redeposited loess with a buried soil (*Gmelin soil*) overlain by a primary full-glacial loess with an associated Chernozem (Mollisol), forming the surface of the second terrace.

Bibliography

Anikovich, M. V., Sinitsyn, A. A., Hoffecker, J. F., Holliday, V. T., Popov, V. V., Lisitsyn, S. N., Forman, S. L., Levkovskaya, G. M., Pospelova, G. A., Kuz'mina, I. E., Burova, N. D., Goldberg, P., Macphail, R. I., Giaccio, B., and Praslov, N. D., 2007. Early Upper Paleolithic in Eastern Europe and implications for the dispersal of modern humans. *Science*, **315**(5809), 223–226.

Efimenko, P. P., 1958. *Kostenki I*. Moscow: Izdatel'stvo Akademii nauk SSSR.

Giaccio, B., Isaia, R., Fedele, F. G., Di Canzio, E., Hoffecker, J., Ronchitelli, A., Sinitsyn, A. A., Anikovich, M., Lisitsyn, S. N., and Popov, V. V., 2008. The Campanian Ignimbrite and Codola tephra layers: two temporal/stratigraphic markers for the early Upper Palaeolithic in southern Italy and Eastern Europe. *Journal of Volcanology and Geothermal Research*, **177**(1), 208–226.

Grishchenko, M. N., 1976. *Pleistotsen i golotsen basseina Verkhnego Dona [Pleistocene and Holocene of the Upper Don Basin]*. Moscow: Nauka.

Hoffecker, J. F., 2002. *Desolate Landscapes: Ice-Age Settlement in Eastern Europe*. New Brunswick: Rutgers University Press.

Holliday, V. T., Hoffecker, J. F., Goldberg, P., Macphail, R. I., Forman, S. L., Anikovich, M., and Sinitsyn, A., 2007. Geoarchaeology of the Kostenki-Borshchevo sites, Don River Valley, Russia. *Geoarchaeology*, **22**(2), 181–228.

Kholmovoi, G. V., and Nesterova, E. V., 2001. *Pleistotsenovye otlozheniya Kostenkovsko-Borshchevskogo paleoliticheskogo raiona [Pleistocene Deposits of the Kostenki-Borshchevo Paleolithic Region]*. Voronezh: Voronezhskii Gosudarstvennyi Universitet.

Klein, R. G., 1969. *Man and Culture in the Late Pleistocene: A Case Study*. San Francisco: Chandler.

Lazukov, G. I., 1957. Geologiya stoyanok Kostenkovsko-Borshevskogo raiona [Geology of the sites of the Kostenki-Borshchevo region]. *Materialy i issledovaniya po arkheologii SSSR*, **59**, 135–173.

Praslov, N. D., 1982. Istoriya izucheniya paleolita Kostenkovsko-Borshchevskogo raiona i slozhenie kostenkovskoi shkoly [History of the study of the Paleolithic of the Kostenki-Borshchevo region and the making of the Kostenki School]. In Praslov, N. D., and Rogachev, A. N. (eds.), *Paleolit Kostenkovsko-Borshchevskogo raiona na Donu 1879–1979: Nekotorye itogi polevykh issledovanii [The Paleolithic of the Kostenki-Borshchevo Region on the Don 1879–1979]*. Leningrad: Nauka, pp. 7–13.

Praslov, N. D., and Rogachev, A. N. (eds.), 1982. *Paleolit Kostenkovsko-Borshchevskogo raiona na Donu 1879–1979: Nekotorye itogi polevykh issledovanii [The Paleolithic of the Kostenki-Borshchevo Region on the Don 1879–1979: Some Results from Field Studies]*. Leningrad: Nauka.

Pyle, D. M., Ricketts, G. D., Margari, V., van Andel, T. H., Sinitsyn, A. A., Praslov, N. D., and Lisitsyn, S., 2006. Wide dispersal and deposition of distal tephra during the Pleistocene 'Campanian Ignimbrite/Y5' eruption, Italy. *Quaternary Science Reviews*, **25** (21–22), 2713–2728.

Rogachev, A. N., 1957. Mnogosloinye stoyanki Kostenkovsko-Borshevskogo raiona na Donu i problema razvitiya kul'tury v epokhy verkhnego paleolita na Russkoi ravnine [Multi-layered sites of the Kostenki-Borshchevo region on the Don and the problem of the development of culture of the Upper Paleolithic epoch on the Russian Plain]. *Materialy i issledovaniya po arkheologii SSSR*, **59**, 9–134.

Sinitsyn, A. A., Praslov, N. D., Svezhentsev, Y. S., and Sulerzhitskii, L. D., 1997. Radiouglerodnaya khronologiya verkhnego paleolita Vostochnoi Evropy [Radiocarbon chronology of the Upper Paleolithic of Eastern Europe]. In Sinitsyn, A. A., and Praslov, N. D. (eds.), *Radiouglerodnaya khronologiya paleolita vostochnoi Evropy i Severnoi Azii: problemy i perspektivy [Radiocarbon Chronology of the Paleolithic of Eastern Europe and Middle Asia: Problems and Perspectives]*. St. Petersburg: Rossiiskaia akademiia nauk, Institut istorii material'noi kul'tury, pp. 21–66.

Velichko, A. A., 1961. *Geologicheskii vozrast verkhnego paleolita tsentral'nykh raionov russkoi Ravniny [Geologic Age of the Upper Paleolithic of the Central Region of the Russian Plain]*. Moscow: Izdatel'stvo Akademii nauk SSSR.

KOSTER SITE, ILLINOIS

Edwin R. Hajic
GeoArc Research, Inc., Santa Fe, NM, USA

Koster site

Koster (11GE4) is an archaeological site located at the foot of the eastern bluff line of the lower Illinois River Valley in west central Illinois, USA (Brown and Vierra, 1983). It contains at least 23 stratigraphically distinct Early Archaic to Mississippian cultural deposits buried to depths in excess of 10 m. The site provides a nearly continuous Holocene record of deposition, soil formation, and human occupation, and between 1969 and 1978, it became the cornerstone of pioneering interdisciplinary research conducted by the Foundation for Illinois Archeology, Northwestern University, and the Center for American Archeology. Recognizing the significance of buried pristine cultural deposits rich in plant and animal remains with a cumulative record that spanned more than eight millennia at a single location, Stuart Struever and James Brown focused their research on identifying cultural adaptations (e.g., social, economic, technological) and exploring their links to changing Holocene climate and valley environments. In the process, cultural phases of the then little known Archaic period were defined.

Within this cultural framework, major advances applicable to the midcontinent and beyond – all based on the Koster artifact and feature record and local and regional paleoenvironments – were made in understanding cultural adaptations that culminated in the more complex later woodland cultures. Evidence for what at the time were the earliest Midwest house floors, along with thick middens and diverse artifact assemblages, changed ideas about Archaic sedentism and settlement patterns. Not only did archaeobotanical remains reveal the earliest origins of regional cultivation, but they provided evidence for the rise of broad-spectrum subsistence patterns in hunter-gatherer lifeways, with attendant behavioral strategies and patterns for environmental exploitation. Evidence from skeletal remains was used to examine human responses to environmental stresses and changes in social status (Buikstra, 1981).

Koster also is significant in being one of the earliest experiments in a large-scale interdisciplinary archaeological undertaking aimed at understanding cultural adaptations to changing climate and landscape at different scales (Struever and Holton, 1979). Along with archaeologists, the research team included specialists in archaeobotany, malacology, palynology, geology, and computers. Struever also actively engaged the public through field schools and other educational programs, using the high-profile Koster site to draw attention to regional interdisciplinary research at numerous sites in the Lower Illinois Valley.

In addition to its contributions to the interpretation of the archaeological record, Koster provided ideas to advance deep site excavation techniques and design, including deep macroblock excavations. Dewatering wells were installed to draw down the water table and make excavation possible at depth. Conveyor systems and bulldozers were utilized to remove backdirt. Flotation sample collection and processing techniques were improved and then systematically and uniformly applied during years of excavation. Piece-plotting of all artifacts and debris was employed as a large-scale experiment.

Cultural deposits at Koster are buried and preserved within a southeast-facing prism of valley margin colluvium, situated within the mouth of a small bedrock valley occupied by Koster Creek, and an associated alluvial fan. Colluvial and fan deposits consist almost entirely of silt derived from loess eroded from surrounding uplands by raindrop and sheetflood processes and deposited by sheetflood sedimentation. The entire alluvial fan and part of the colluvial wedge aggraded on a late Pleistocene terrace of the Illinois River valley. Koster Creek drains into a paleochannel lake basin on a second, younger pre-Holocene terrace beyond fan limits. Thus, evolution of the entire Holocene Koster slope/fan depositional system, while open, was independent of, and isolated from, Holocene geomorphic fluvial change in the Illinois Valley.

Forty-four radiocarbon ages from macroblock excavations primarily in colluvium document moderate sedimentation rates for the early Holocene, with a pattern of initially rapid but overall declining sedimentation rates from about 8450 ^{14}C yr BP through the remainder of the Holocene. Superimposed upon this is a series of at least seven sediment-soil cycles, individually characterized by continuous sedimentation at progressively decreasing rates (Hajic, 1990). Most cycles culminate in cumulic A horizons built up over a period on the order of several hundred years, as sedimentation never actually ceased. The oldest and two youngest cycles culminate in soils with structural B horizons that developed on the order of 500–1500 years under a regime of limited sediment accumulation. Most of the younger buried soils are truncated by sheetflood erosion, accompanied by gullying and development of stone lines of cultural debris. All buried soils have associated distinct cultural deposits, but a greater number of distinct cultural deposits are not associated with soil sola (i.e., A and B horizons that were created by the same soil-forming processes; singular = solum). Anthropogenic enrichment of buried soil A horizons is common.

The character of the sediment sequence at Koster is the result of a combination of extrinsic and intrinsic factors operating at different time scales (Hajic, 1990). Overall decreasing sedimentation rate throughout most of the Holocene is attributed largely to changing geometric relationships between eroding loessial slopes and the colluvial slope, although changes to and from more open vegetation on hillslopes with less than a 4° degree slope at the onset and end of the middle Holocene, respectively, are a contributing factor. The timing of individual sediment soil cycles at Koster corresponds with other colluvial records in the lower Illinois Valley region and broadly with alluvial fan records as far west as western Iowa (Wiant et al., 1983). Regional patterning in colluvial sedimentation during the Holocene compared to independent regional paleoenvironmental records suggests there is a biogeomorphic response to a shift toward more arid conditions that improves the effectiveness of raindrop and sheetflood erosion, thus initiating an increase in soil erosion of upland slopes and colluvial slope sedimentation that marks the beginning of each cycle. Slowing sedimentation rates culminating in soil formation reflects a gradual shift back toward relatively wetter conditions. Late Holocene erosional episodes that truncate soils and some cultural deposits are an intrinsic response to the eclipse of a threshold colluvial slope angle between 7° and 9°.

For further reading, see Brown and Struever (1973), but also Houart (1971), Asch et al. (1972), Cook (1976), Butzer (1977, 1978), Buikstra (1981), Wiant et al. (1983), and Hajic (1990).

Bibliography

Asch, N. B., Ford, R. I., and Asch, D. L., 1972. *Paleoethnobotany of the Koster Site: The Archaic Horizons. Reports of Investigations 24*. Springfield: Illinois State Museum.

Brown, J. A., and Struever, S., 1973. The organization of archeological research: An Illinois example. In Redman, C. L. (ed.), *Research and Theory in Current Archeology*. New York: John Wiley, pp. 261–280.

Brown, J. A., and Vierra, R. K., 1983. What happened in the middle Archaic? Introduction to an ecological approach to Koster site archaeology. In Phillips, J. L., and Brown, J. A. (eds.), *Archaic Hunters and Gatherers in the American Midwest*. New York: Academic, pp. 165–195.

Buikstra, J. E., 1981. Mortality practices, paleodemography, and paleopathology: A case study from the Koster Site (Illinois). In Chapman, R., Kinnes, I., and Randsborg, K. (eds.), *The Archaeology of Death*. Cambridge: Cambridge University Press, pp. 123–132.

Butzer, K. W., 1977. *Geomorphology of the Lower Illinois Valley as a Spatial-Temporal Context for the Koster Archaic Site*. Reports of Investigations 34. Springfield: Illinois State Museum.

Butzer, K. W., 1978. Changing Holocene environments at the Koster site: A geo-archaeological perspective. *American Antiquity*, **43**(3), 408–413.

Cook, T. G., 1976. *Koster: An Artifact Analysis of Two Archaic Phases in West Central Illinois*. Prehistoric Records 1. Koster Research Reports 3. Evanston: Northwestern University Archaeological Program.

Hajic, E. R., 1990. *Koster Site Archaeology: Stratigraphy and Landscape Evolution. Research Series 8*. Kampsville: Center for American Archeology.

Houart, G. L., 1971. *Reports of Investigations 22. Koster: A Stratified Archaic Site in the Lower Illinois Valley*. Springfield: Illinois State Museum.

Struever, S., and Holton, F. A., 1979. *Koster: Americans in Search of Their Prehistoric Past*. Garden City, NY: Anchor Press/Doubleday.

Wiant, M. D., Hajic, E. R., and Styles, T. R., 1983. Napoleon Hollow and Koster Site stratigraphy. In Philips, J. L., and Brown, J. A. (eds.), *Archaic Hunters and Gatherers in the American Midwest*. New York: Academic, pp. 147–164.

Cross-references

Colluvial Settings
Sedimentology
Soils

L

LA MICOQUE

Christopher E. Miller
Institute for Archaeological Sciences, Senckenberg Centre for Human Evolution and Paleoenvironment, University of Tübingen, Tübingen, Germany

La Micoque is a Paleolithic site located in the Dordogne region of southwestern France. The site is well known for its Acheulian and particularly its Middle Paleolithic artifacts. The site lends its name to the Micoquian industry of stone tools.

Situated along the left bank of the Manaurie valley, 500 m from its confluence with the Vézère River, La Micoque sits below a cliff of Coniacian limestone (Late Cretaceous). The site was first discovered in 1895 by the landowner and subsequently excavated by Chauvet and Rivière in 1896, Capitan in 1896, Harlé in 1897, Peyrony in 1898 and 1929–1932, Coutil in 1903–1905, Cartailhac in 1905, and Hauser in 1906–1907. Bordes excavated the site in 1956, and it was most recently investigated by Debénath and Rigaud between 1983 and 1996.

The lowest cultural layers contain the transition from Acheulian to Mousterian industries (the so-called Tayacian), which has been dated by Electron Spin Resonance (ESR) on horse teeth to between 241 ± 15 and 288 ± 10 ka (Schwarcz and Grün, 1988). The site also contains small, elongated, bifacially worked hand axes, known as Micoquian-type hand axes, in addition to scrapers with quina retouch and Mousterian points.

Capitan and Hauser were the first excavators to describe the stratigraphy (Capitan, 1896); however, the stratigraphic system of Peyrony, first established in 1933, has become the standard for the site (Peyrony, 1938). He defined several horizontal layers, starting with A at the base and finishing with M at the top. He identified layers with angular limestone clasts as *éboulis* (rock scree or talus) and layers with rounded cobbles as having a fluvial origin. Breuil (1938) criticized Peyrony's interpretation of the rounded cobbles and suggested that their rounding was a result of cryoclastism related to cryoturbation and solifluction. Bordes, Laville, and Rigaud adopted this interpretation and suggested that the deposits formed within a rock-shelter, whose roof no longer exists (Laville, 1973, 197–226). La Micoque became a key site for the development of Laville's climatostratigraphic synthesis of cave and rock-shelter sequences in southwestern France. At La Micoque and other sites, he interpreted the *éboulis* layers as representing cold, glacial periods and the reddish sandy-clay layers as representing in situ formation of soils during interstadials and interglacials.

Texier, in a recent reassessment of site formation processes at La Micoque (2009), questions most of the previous interpretations. Like Peyrony, he argues, based on sedimentological data, that the majority of the site was formed by fluvial action, as indicated by rounded grains and cobbles, graded bedding, and cross-stratification. Some diamictic layers, formed by colluvation, originated from the limestone cliff backing the site. Taken together, the geoarchaeological evidence strongly suggests that La Micoque is not a former rock-shelter, but rather the remnant of a former fluvial terrace of the Manaurie River, now a small stream.

Bibliography

Breuil, H., 1938. Des causes de fracture du silex et du pseudo-roulis des pierres calcaires dans des couches résiduelles de La Micoque et autres lieux. *Bulletin de la Société préhistorique de France*, **35**(6), 283–288.

Capitan, L., 1896. La station acheuléenne de la Micoque (Dordogne). *Bulletins de la Société d'anthropologie de Paris*, **7**(7), 529–532.

A.S. Gilbert (ed.), *Encyclopedia of Geoarchaeology*, DOI 10.1007/978-1-4020-4409-0,

Laville, H., 1973. *Climatologie et chronologie du paléolithique en Périgord: étude sédimentologique de dépôts en grottes et sous abris*. Thèse de Doctorat Sc. nat. Bordeaux: Université de Bordeaux 1, pp. 197–226.
Peyrony, D., 1938. La Micoque. Les fouilles récentes. – Leur signification. *Bulletin de la Société préhistorique de France*, **35**(6), 257–283.
Schwarcz, H. P., and Grün, R., 1988. ESR dating of level L 2/3 at La Micoque (Dordogne), France: excavations of Debénath and Rigaud. *Geoarchaeology*, **3**(4), 293–296.
Texier, J.-P., 2009. *Histoire géologique de sites préhistoriques classiques du Périgord: une vision actualisée: La Micoque, la grotte Vauffrey, Le Pech de l'Azé I et II, La Ferrassie, l'abri Castenet, Le Flageolet, Laugerie Haute*. Paris: Éditions du Comité des travaux historiques et scientifiques.

LAKE MUNGO AND WILLANDRA

Jim Bowler
Earth Sciences, University of Melbourne, Parkville Campus, VIC, Australia

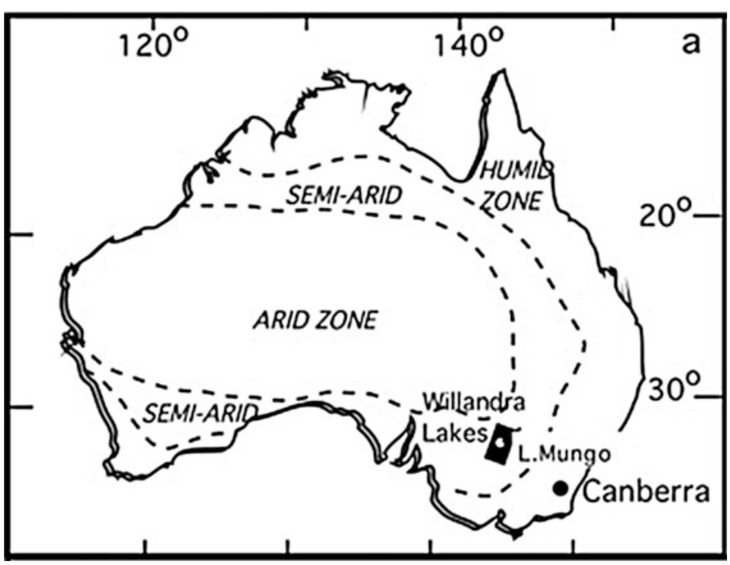
Definition and introduction

Lake Mungo is located in western New South Wales, Australia (Figure 1), and represents a dry lake bed that forms part of the Willandra Lakes Region, a series of 19 relict lake basins which was named in 1981 a World Heritage Site for both natural and cultural value. At Lake Mungo, early evidence of human occupation has been found within the large and presently eroding dune, or lunette, that lies along the eastern shore of the former lake. Also at Lake Mungo, geoarchaeology has played a major role in helping to establish the date and ancient environment within which the early inhabitants lived.

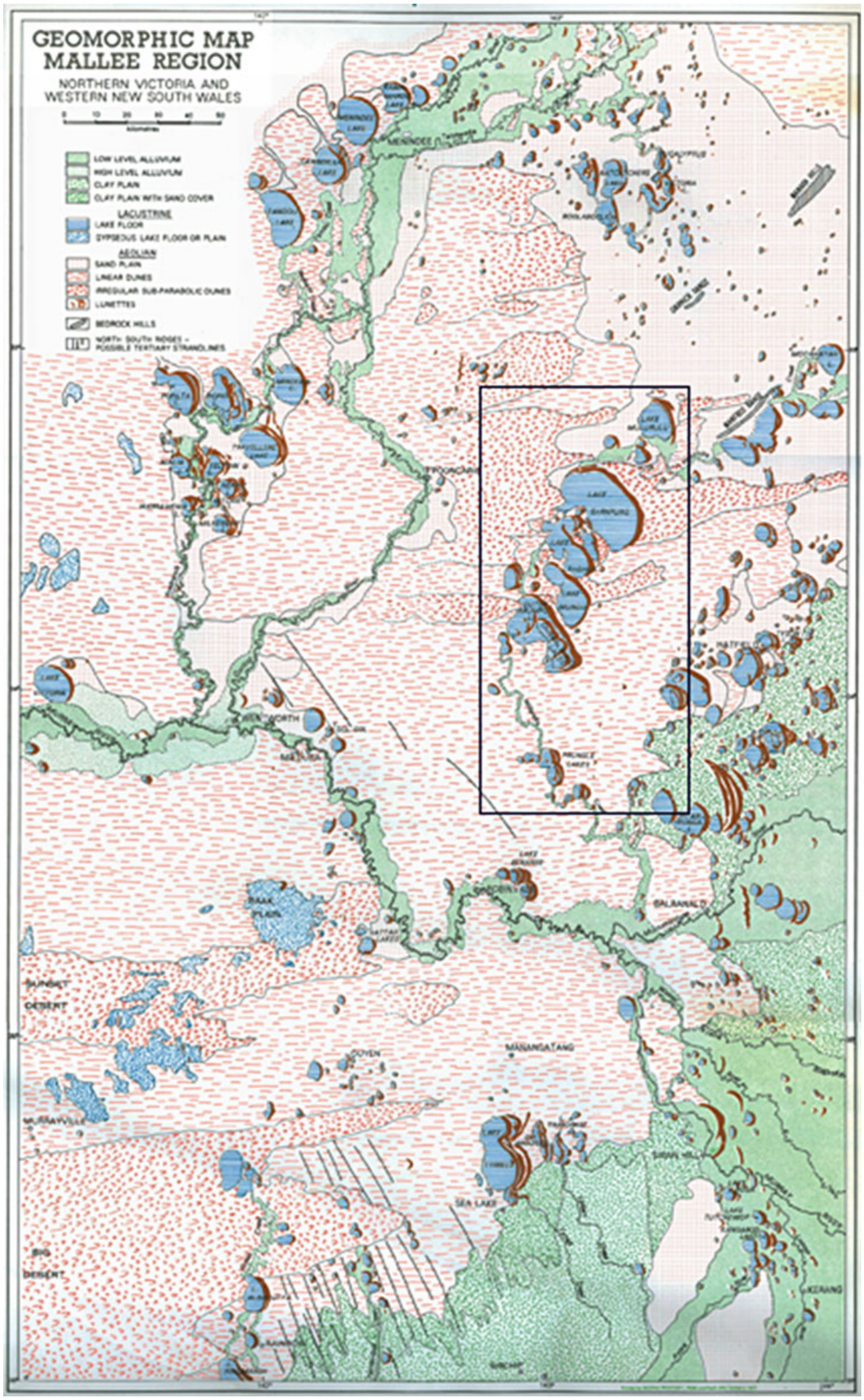
Lake Mungo and the Willandra Lakes Region in which it lies are in some ways analogous to the African Rift Valley sites. Both are open, vast in expanse, and deep in time scale. Both require expansive geomorphic mapping as well as detailed stratigraphic analyses. At Lake Mungo, joint teamwork in geology and archaeology has been highly successful in reconstructing habitation in early Australia.

The Willandra Lakes landscape preserves a series of dry basins formerly supplied by the Lachlan River, which derived its waters from catchments in the southeastern highlands near Canberra (Figure 2). These lake basins were mapped and named in the course of a paleoclimatic study of lakes and dunes of the last glacial cycle (Bowler, 1971). The incipient stages in the growth of the Mungo lunette date from 150,000 years ago (Bowler and Price, 1998), when the large crescent-shaped dune along the eastern lake margin began to form from the blowing of sand off the lakeshore (Figures 3 and 4). Understanding of these lakes was made possible by the definition of lunette formation processes (Bowler, 1973). Lunette landforms are of special relevance, as they (1) record hydrologic change in their internal alternation of sand layers deposited during moist periods and clay layers laid down during dry phases and (2) the alkalinity of their sediments that has proved favorable to the preservation of archaeological remains.

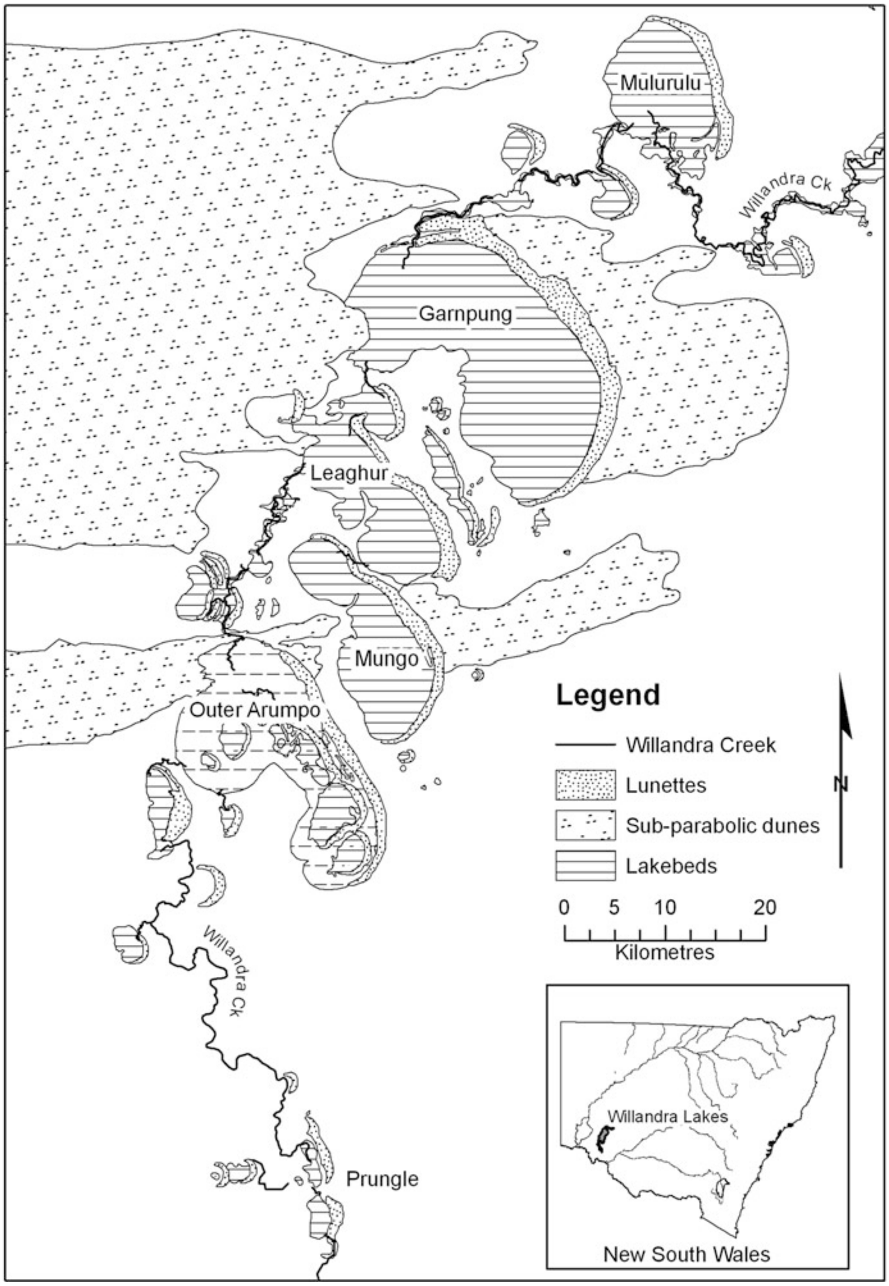
The Golgol layer in which the lunette began was followed by the Mungo layer (50–25 ka), which saw the arrival of human groups that settled along the lake margins



Lake Mungo and Willandra, Figure 1 Map showing the location of the Willandra World Heritage Region in semiarid southeastern Australia.

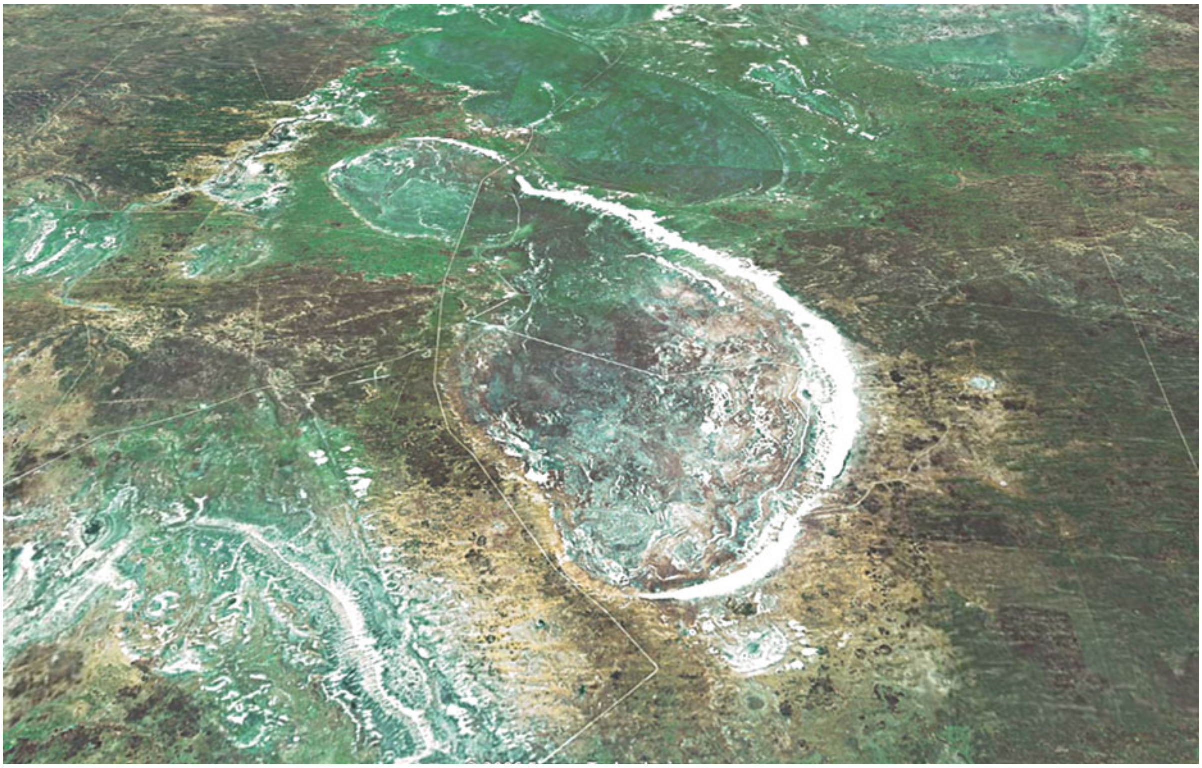


Lake Mungo and Willandra, Figure 2 Geomorphic map of the Mallee dunefields and lunette-lake basins in southeastern Australia. Lying northeast of the Darling and Murray River confluence, the Willandra lakes were fed by a former Lachlan River channel.

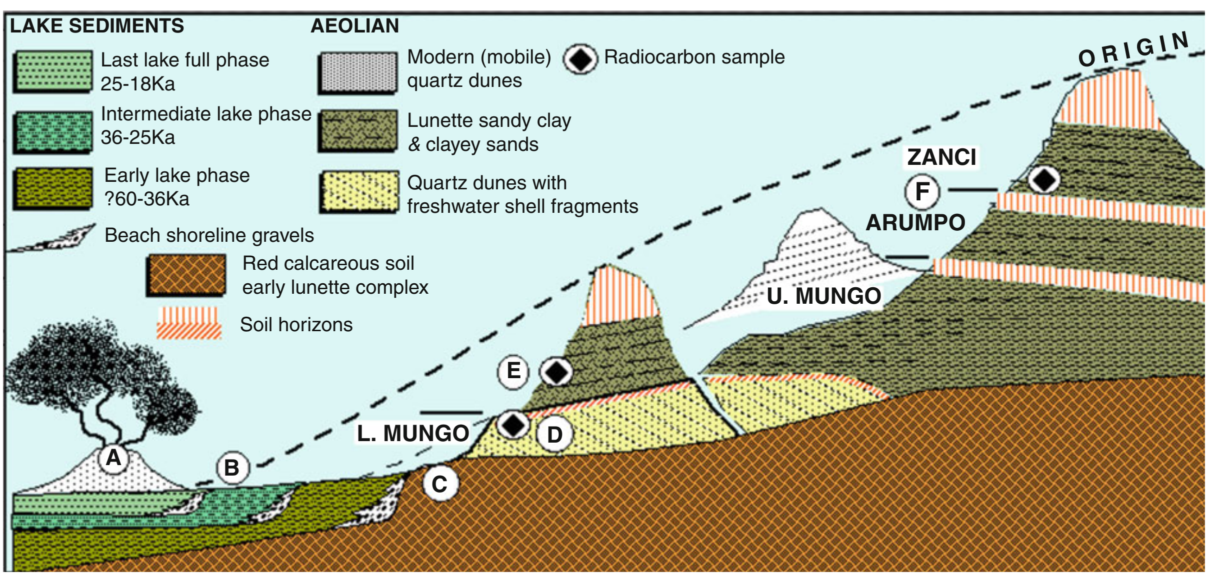


Lake Mungo and Willandra, Figure 3 The Willandra chain of lakes forms a linking overflow system set within fossil dunefields. Lunettes on the eastern sides preserve a 50,000-year record of human occupation in the context of Ice Age environmental change.

within the growing lunette. The Mungo layer is the most archaeologically significant, as its evidence for human colonization is the earliest known to date in Australia. The slopes of the dunes remained mostly stable with vegetation cover over long periods, but draining and drying of the lake starting at the Last Glacial Maximum, ca. 20–18 ka (Bowler, 1998), exposed the slopes to winds that began mobilizing the dunes and eroding them severely, so that the buried remains continuously become exposed and, as in the African Rift Valley, visible to archaeologists (Figure 5). Presently, erosion by high-intensity storms provides both positive and negative opportunities: positive in the sense that huge areas of sediments are constantly worn down presenting new surfaces for inspection, but negative in the sense that cultural materials, once exposed, are rapidly destroyed by later storm events unless they are found, evaluated, and where necessary preserved or collected.



Lake Mungo and Willandra, Figure 4 Oblique satellite view looking north over Lake Mungo. The lunette extends 25 km along the eastern lakeside and is subject to intensive erosion, which continuously reveals a rich tapestry of geological and archaeological information. The location of the main burial sites lies near the southern termination of the lunette. Image from Google Earth.



Lake Mungo and Willandra, Figure 5 Diagrammatic cross section through the eastern side of the Lake Mungo lunette. Layered lunette sentiments deflated from the lake floor lie downwind of the lakeshore beach and gravel facies. Episodic changes spanning the last 60,000 years (Mungo to Zanci age units) are inset into the older Golgol unit dating to the previous glacial cycle.

In 1969, the partially cremated remains of a young woman – Mungo Lady – were found deep within the lakeshore lunette, and this discovery opened the door to a new phase of Australia's archaeological history (Bowler et al., 1970). Soon after, in 1974, an articulated and ochre-anointed male burial was uncovered nearby – Mungo Man – and this new find brought increased attention and significance to the site. Both burials indicated ritual behavior, and they were dated to 41,000 years ago (Bowler et al., 1972, 2003; Gillespie, 1998).

In 2003, the discovery of a complex of human footprints (Webb et al., 2006) preserved in saline muds of the Zanci layer just south of the Lake Garnpung basin and dated to around 21 ka by OSL added a new component of international interest. The hardpan into which the footprints were impressed comprises layers of silty clay cemented by an unusual mineral, hydromagnesite. Erosion had exposed 89 of the 123 human footprints at the moment of discovery, most of which form eight different tracks. The substrate on which the humans walked must have been unconsolidated and intermittently wet as it took mostly excellent impressions of feet belonging to a range of individuals that included adults and children.

Summary

The Willandra basins and Lake Mungo constitute a widespread and open archaeological region containing dry lands undergoing active erosion; this erosion provides almost continuous surface exposures. The remains uncovered are of high archaeological value and provide unique opportunities to bring together both natural and cultural history to elucidate patterns of past human-land interaction, which are among the earliest known in Australia. In addition to its science, the region has immense social value in building reconciliation bridges between modern white communities and today's Aboriginal Australians.

Bibliography

Bowler, J. M., 1971. Pleistocene salinities and climatic change: evidence from lakes and lunettes in southeastern Australia. In Mulvaney, D. J., and Golson, J. (eds.), *Aboriginal Man and Environment in Australia*. Canberra: Australian National University Press, pp. 47–65.

Bowler, J. M., 1973. Clay dunes: their occurrence, formation and environmental significance. *Earth-Science Reviews*, **9**(4), 315–338.

Bowler, J. M., 1998. Willandra Lakes revisited: environmental framework for human occupation. *Archaeology in Oceania*. **33**, 156–168.

Bowler, J. M., Price, D. M., 1998. Luminscence dates and stratigraphic analysis at Lake Mungo: review and new perspectives. *Archaeology in Oceania*, **33**, 120–155.

Bowler, J. M., Jones, R., Allen, H., and Thorne, A. G., 1970. Pleistocene human remains from Australia: a living site and human cremation from Lake Mungo, western New South Wales. *World Archaeology*, **2**(1), 39–60.

Bowler, J. M., Johnston, H., Olley, J. M., Prescott, J. R., Roberts, R. G., Shawcross, W., and Spooner, N. A., 2003. New ages for human occupation and climatic change at Lake Mungo, Australia. *Nature*, **421**(6925), 837–840.

Bowler, J. M., Thorne, A. G., and Polach, H. A., 1972. Pleistocene man in Australia: age and significance of the Mungo skeleton. *Nature*, **240**(5375), 48–50.

Gillespie, R., 1998. Alternative timescales: a critical review of Willandra Lakes dating, Australia. *Archaeology in Oceania*, **33**(3), 169–182.

Webb, S., Cupper, M. L., and Robin, R., 2006. Pleistocene human footprints from Willandra Lakes, southeastern Australia. *Journal of Human Evolution*, **50**(4), 405–413.

LANDSCAPE ARCHAEOLOGY

Tim Denham
Archaeological Science Programs, School of Archaeology and Anthropology, The Australian National University, Canberra, ACT, Australia

Definition

Landscape archaeology refers to the understanding of archaeological remains (artifacts, sites, and site complexes) in terms of the wider spatial realms (both physical and meaningful) of past human experience.

Introducing landscape

"Landscape" is an integrated term that encapsulates the environmental and human aspects of a bounded area of land. The environmental aspects include the combined effects of climate, hydrology, landforms, vegetation, and fauna. The human imprint reflects the cumulative effects of cultural processes that have occurred through time, including: the histories of vegetation disturbance, clearance, and planting; earthmoving; settlement; pollution; and so on. In addition to the physical aspects of past landscapes – in terms of both environmental and human processes – a landscape is explicitly or implicitly associated with layers of human meaning and value.

A landscape represents an amalgam of different processes operating over disparate timescales. For instance, landforms and the rocks that comprise a landscape may have formed over million- or billion-year timescales, whereas vegetation and buildings may reflect processes over much shorter annual to centennial timescales.

The boundary (physical) and boundedness (cultural) of a landscape are usually poorly defined and diffuse, both in the abstract and with respect to a particular landscape in the present or the past. Namely, it is often impossible to demarcate clearly a boundary for a landscape on a map, and it is usually impossible for someone standing within a landscape to indicate clearly where one landscape ends and another begins. Despite this ambiguity, the landscape represents an intermediate spatial scale; it is larger than a site or site complex but smaller than a region. In many ways, the landscape represents a human scale of lived experience. Most people, whether they live in a postindustrial, industrial, or traditional society, spend most of their lives within a bounded area, which could be referred to as the landscape of everyday experience.

In sum, a landscape reflects a combination of environmental and human processes that have operated through time and across space. Today, no landscapes are free from the direct or indirect effects of human-induced modification, although the degree and nature of these influences vary greatly. Landscapes are also imbued with layers of cultural meaning that have accrued to the present.

A brief history of landscape archaeology

David and Thomas (2008a, 38) have suggested "landscape archaeology is . . . concerned with the things that locate human existence." Although conceptually appropriate, such a scope is too broad to be methodologically useful or applicable. In many ways, and for most of history, the landscape represented a "human scale" of past lived experience (Denham, 2008). Indeed, the term "landscape" implies a meaningful place for the inhabitants, visitors, or viewers. People lived, and continue to live, in landscapes, even though the physical scale and the degree of mobility within and between landscapes have changed through time. Consequently, landscape archaeology can be considered to be the study of artifacts, features, sites, and site complexes within the broader spatial realms – both physical and meaningful – of past human experience.

Landscape archaeology has undergone considerable transformation and augmentation since it was first coined and applied in the mid-1970s (Aston and Rowley, 1974; David and Thomas, 2008a). Although archaeological concerns with "landscape" are much older, Aston and Rowley's text marks the emergence of "landscape archaeology" as a subdiscipline. From the 1970s onward, various incarnations of landscape archaeology have reflected to a large degree the general trends in archaeological theory within the discipline as a whole. Rather than sequentially replacing each preceding trend, subsequent perspectives have tended to augment the purview of landscape archaeology, resulting in a broad array of conceptual and methodological approaches (Ashmore and Knapp, 1999; David and Thomas, 2008b).

Initially, landscape archaeology was associated with various streams of archaeological science, environmental archaeology, and spatial analysis, reflecting the dominance of processual thought or New Archaeology. These types of approach have tended to focus upon the distributions of artifacts and sites across an area, primarily with respect to environmental features such as landforms, hydrology, soils, and vegetation (e.g., Torrence, 2002). They have also tended to incorporate perspectives from environmental archaeology or geoarchaeology (e.g., Denham, 2008). Explanatory models have prioritized environmental, ecological, economic, and social interpretations to understand observed distributions.

To exemplify, changing human use of the lunette (sand dunes of the eastern shore) at Lake Mungo in rural New South Wales, Australia, has been articulated in terms of fluctuating climates and ensuing lake levels from ca. 50,000 to 46,000 years ago (Bowler et al., 2003). Interpretations of archaeological remains, including human burials, have necessitated a spatial understanding of lunette formation through time. Ongoing investigations are now focusing upon detailed histories of landscape formation and human subsistence for sections of the lunette (pers. comm., Nicola Stern, 2012).

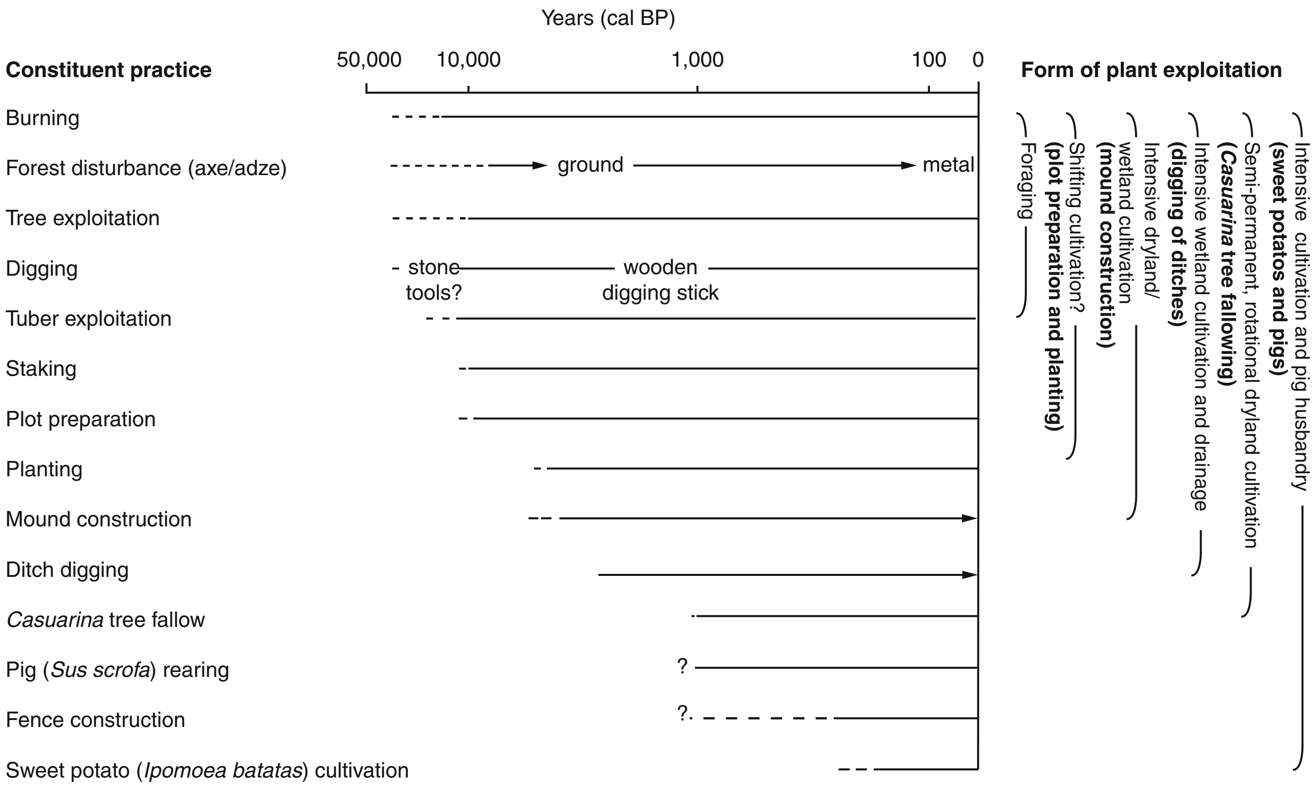
In recent decades, landscape archaeology has broadened to include an array of emergent perspectives including ethnoarchaeology (Ballard, 1994); humanistic, phenomenological, and symbolic interpretations (Tilley, 1994; Bradley, 2000); and political and indigenous critiques (Bender, 1993). These perspectives draw on diverse intellectual traditions to prioritize the meanings attributed to places, including the distribution of archaeological finds within the landscape. Although sometimes criticized, these approaches to landscape archaeology usually represent serious attempts to convey a sense of the ways people were connected to places in the past.

Following the above, landscape archaeology can be viewed as having two main streams: (1) the empirical aspects of human-environment interactions within a bounded area in the past and (2) the ways in which archaeologists today consider landscapes to have been meaningful to the people who inhabited them in the past. A third minor theme, not dwelt upon here, is the study of landscapes and landscape depictions as historical, political, symbolic, or colonial representations; this is a relatively recent development within archaeology that can trace its intellectual roots to geography (Cosgrove and Daniels, 1988; Cosgrove, 1998).

Landscape as a product of human-environment interactions

Landscape archaeology is primarily concerned with the environmental context of human activities in the past. Here, landscape is taken in terms of its physicality. Consequently, aspects of landscape archaeology mirror those of environmental archaeology and geoarchaeology in seeking to characterize how past environments structured, and have in turn been structured by, past human behavior. Accordingly, landscape archaeology is concerned with the recursive and mutually determining nature of human-environment interactions in the past.

In terms of a differentiating characteristic, landscape archaeology takes as its object of study how past human activities occurred and were structured *across* space within a bounded area, rather than at the scale of individual sites or at the scale of interregional and intercontinental comparison. In this way, landscape archaeology



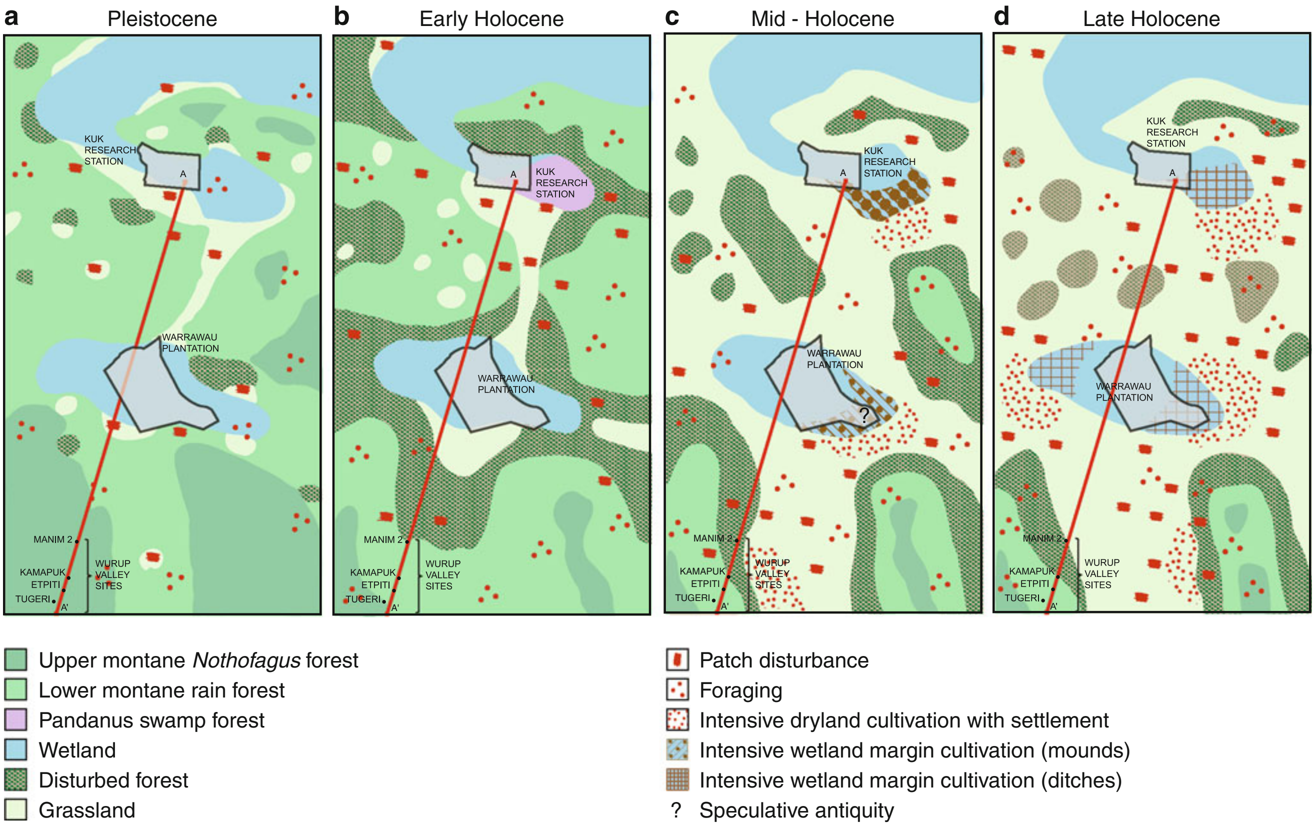
Landscape Archaeology, Figure 1 Chronology of practices and forms of plant exploitation reconstructed for the Upper Wahgi Valley, Papua New Guinea, using multidisciplinary lines of evidence.

provides a middle scale of analysis linking finds and formation processes at individual sites to larger-scale trends. Landscape archaeology is not just an intermediate spatial scale of analysis; it also provides a methodological bridge comparable to, but different from, intermediate conceptual formulations such as middle-range theory (Raab and Goodyear, 1984) and contextual or reflexive archaeology (Hodder, 1999).

A useful methodological tool to unravel the complexities of how people lived in a landscape is the concept of "practice" (Bourdieu, 1990; Barrett, 1994; Denham, 2008; Jusseret, 2010). In archaeology, practices represent human actions in the past, including habitual modes of behavior and dispositions, as well as individual idiosyncrasies. Practices become inscribed in the landscape through time, providing sequential evidence of human-environment interactions in the past. The concept of practice is a useful way to overcome various dualisms, or binary divisions, that permeate the study of human-environment interactions in the past and present, because practices represent the nexus of these interactions (Denham, 2008).

Evidence of practices can be derived from multiple disciplines, each with its own methodological limitations. For example, archaeological and geophysical surveys provide information on the distribution of archaeological materials across the surface and subsurface, respectively, of a landscape. Archaeological excavations provide chronologically specific site-based information, although in some cases, large expanses of a landscape can be exposed and excavated simultaneously. In contrast, paleoecology provides a conflated record of vegetation history and burning for a local and extra-local area that can be used to infer what people were doing in the past but with varying degrees of chronological and geographical specificity. Taken together, archaeological and paleoecological records can provide robust reconstructions of how people lived in and changed landscapes through time.

To exemplify, multidisciplinary evidence at several occupation and wetland archaeological sites in the Upper Wahgi Valley of the Papua New Guinea highlands has enabled a chronology of practices to be reconstructed (Figure 1; Denham and Haberle, 2008; Denham, 2009). Different disciplines provide evidence of different types of practice in the past; for example, paleoecological records indicate burning in the Late Pleistocene; archaeological excavations show evidence for numerous practices, including digging, planting, and fencing; and residue analysis indicates the exploitation of tuberous plants in the early Holocene. Individual practices can be bundled together to show how agriculture emerged and was transformed in the Upper Wahgi Valley through time.



Landscape Archaeology, Figure 2 Landscape reconstructions for multiple time slices in the Upper Wahgi Valley landscape: (**a**) terminal Pleistocene, ca. 12,000 cal BP; (**b**) early Holocene, ca. 9,000 cal BP; (**c**) mid-Holocene, ca. 6,500 cal BP; and (**d**) late Holocene, ca. 2,500 cal BP (Denham and Haberle, 2008: Figure 6). The *red line* is 17 km long, and several archaeological sites along this transect are named. Note the different land use practices across the landscape, ranging from localized patch disturbance to intensive cultivation, and the resultant transformations of vegetation, ranging from disturbed montane rainforest in the Pleistocene to extensive grasslands from the mid-Holocene.

The same multidisciplinary evidence can be represented spatially to illustrate how people lived across the landscape at specific times in the past (Figure 2). Although creative, these synchronic reconstructions, or time slices, rely upon relatively high-resolution records from several archaeological sites, including rock-shelters and wetland sites, as well as paleoecological records from multiple sites. The multidisciplinary records shed light on the types of practice occurring in, as well as the effects of those practices upon, different parts of the landscape. These reconstructions provide readily interpretable impressions of how people lived in landscapes in the past.

The meanings of landscape

Landscape archaeology has increasingly become concerned with the ways in which past landscapes, or the places people inhabited, were meaningful to the people who lived there. Here, the landscape is not conceived in terms of its physicality, but as a meaningful realm of past human experience (following Relph, 1976). Such perspectives invariably shift the emphasis from physical remains of past human activities to more conceptual and interpretative concerns. They should still be reliant, however, on the spatial distribution of archaeological remains together with any associated paleoenvironmental data to infer how people meaningfully conceived, lived in, and used that landscape.

The interpretation of the human dimension within landscape archaeology leads away from an empirical basis to more interpretative concerns in order to infer the ways in which people made their world meaningful. In these types of phenomenologically-informed archaeological discourses, the term "world" does not refer to the realm of entities and things as they physically occur in time and space, namely, the empirical world; rather, it refers to realms of meaning, namely, as things and entities are made meaningful and understood by people. Phenomenologically informed landscape archaeologies are diverse and draw on a range of different concepts, including embodiment, temporality, place, sensory experience, and poetics (Tilley, 2008).

To exemplify, renewed excavations at Stonehenge and other monuments of the early Wessex landscape in southern England have employed ethnographic analogies to infer how the landscape was meaningful to people in the past (Parker Pearson et al., 2006). Different monuments and landforms have been mapped and archaeologically investigated to infer the ways in which people of the mid-third millennium BC conceived domains of the living and domains of the dead within the landscape. From this perspective, the stone structures at Stonehenge are associated with the dead, whereas comparable timber structures at Durrington Walls, Britain's largest henge monument, are associated with ceremonies for the living.

Although most clearly articulated in post-processual debates, the adoption of perspectives to understand or rationalize past human behaviors has, either explicitly or implicitly, always been part of archaeological interpretation. Earlier debates tended to focus on the economic and ecological determinants of human behaviors, such as resource exploitation, whereas more recent decades have witnessed considerable diversification in interpretative frameworks. Phenomenologically-informed perspectives have been at the forefront of conceptual developments within landscape archaeology.

Summary: bridging the divide

Although the two main streams of landscape archaeology appear to be very different, they are complementary and should be considered to represent different emphases. Any historical understanding of landscapes in their physicality, namely, as empirical phenomena, necessitates an interpretation of how they formed or how they came to be; namely, there is always a desire to understand "how" and "why" people engaged in certain types of activity in the past. Similarly, any interpretation of how landscapes may have been meaningful to past inhabitants should be structured by knowledge about changing human-environment interactions within those landscapes in the past. Both approaches to landscape archaeology are predicated on empirically derived knowledge of past human-environment interactions, as well as upon interpretations that seek to understand human behavior in the past, that is, how past landscapes were meaningful to the inhabitants.

Bibliography

Ashmore, W., and Knapp, A. B. (eds.), 1999. *Archaeologies of Landscape: Contemporary Perspectives*. Oxford: Blackwell.

Aston, M., and Rowley, T., 1974. *Landscape Archaeology: An Introduction to Fieldwork Techniques on Post-Roman Landscapes*. Newton Abbot: David and Charles.

Ballard, C., 1994. The centre cannot hold. Trade networks and sacred geography in the Papua New Guinea highlands. *Archaeology in Oceania*, **29**(3), 130–148.

Barrett, J. C., 1994. *Fragments from Antiquity: An Archaeology of Social Life in Britain, 2900–1200 B.C*. Oxford: Blackwell.

Bender, B. (ed.), 1993. *Landscape: Politics and Perspectives*. Providence/Oxford: Berg.

Bourdieu, P., 1990. *The Logic of Practice*. Cambridge: Polity.

Bowler, J. M., Johnston, H., Olley, J. M., Prescott, J. R., Roberts, R. G., Shawcross, W., and Spooner, N. A., 2003. New ages for human occupation and climatic change at Lake Mungo, Australia. *Nature*, **421**(6925), 837–840.

Bradley, R., 2000. *An Archaeology of Natural Places*. London: Routledge.

Cosgrove, D. E., 1998. *Social Formation and Symbolic Landscape*. Madison: University of Wisconsin Press.

Cosgrove, D. E., and Daniels, S. (eds.), 1988. *The Iconography of Landscape*. Cambridge: Cambridge University Press.

David, B., and Thomas, J., 2008a. Landscape archaeology: introduction. In David, B., and Thomas, J. (eds.), *Handbook of Landscape Archaeology*. Walnut Creek: Left Coast Press, pp. 27–43.

David, B., and Thomas, J. (eds.), 2008b. *Handbook of Landscape Archaeology*. Walnut Creek: Left Coast Press.

Denham, T. P., 2008. Environmental archaeology: interpreting practices-in-the-landscape through geoarchaeology. In David, B., and Thomas, J. (eds.), *Handbook of Landscape Archaeology*. Walnut Creek: Left Coast Press, pp. 468–481.

Denham, T. P., 2009. A practice-centred method for charting the emergence and transformation of agriculture. *Current Anthropology*, **50**(5), 661–667.

Denham, T. P., and Haberle, S. G., 2008. Agricultural emergence and transformation in the Upper Wahgi valley during the Holocene: theory, method and practice. *The Holocene*, **18**(3), 481–496.

Hodder, I., 1999. *The Archaeological Process: An Introduction*. Oxford: Blackwell.

Jusseret, S., 2010. Socializing geoarchaeology: insights from Bourdieu's theory of practice applied to Neolithic and Bronze Age Crete. *Geoarchaeology*, **25**(6), 675–708.

Parker Pearson, M., Pollard, J., Richards, C., Thomas, J., Tilley, C., Welham, K., and Albarella, U., 2006. Materializing Stonehenge: the Stonehenge Riverside Project and new discoveries. *Journal of Material Culture*, **11**(1–2), 227–261.

Raab, L. M., and Goodyear, A. C., 1984. Middle-range theory in archaeology: a critical review of origins and applications. *American Antiquity*, **49**(2), 255–268.

Relph, E. C., 1976. *Place and Placelessness*. London: Pion.

Tilley, C., 1994. *A Phenomenology of Landscape: Places, Paths and Monuments*. Providence/Oxford: Berg.

Tilley, C., 2008. Phenomenological approaches to landscape archaeology. In David, B., and Thomas, J. (eds.), *Handbook of Landscape Archaeology*. Walnut Creek: Left Coast Press, pp. 271–276.

Torrence, R., 2002. Cultural landscapes on Garua Island, Papua New Guinea. *Antiquity*, **76**(293), 766–776.

Cross-references

Geomorphology
Lake Mungo and Willandra
Paleoenvironmental Reconstruction
Stonehenge

LEAD ISOTOPES

A. Mark Pollard
Research Laboratory for Archaeology and the History of Art, School of Archaeology, University of Oxford, Oxford, UK

Definition

Lead isotopes. The four stable isotopes of lead are ^{204}Pb, ^{206}Pb, ^{207}Pb, and ^{208}Pb. In geochemistry, the isotopes are usually measured and discussed as the ratios to the ^{204}Pb value, but in archaeology, the ratios of ^{206}Pb/^{204}Pb, ^{206}Pb/^{207}Pb, and ^{208}Pb/^{207}Pb are used.

Provenance. For a metal object, the term refers to the metalliferous ore source from which the metal is derived.

Cupellation. The process by which silver is extracted from argentiferous galena or naturally occurring lead sulfide (PbS).

Fractionation. A process by which the isotopic ratio is altered.

LIA. Lead isotope analysis.

TIMS. Thermal ionization mass spectrometry.

HR-ICP-MS. High-resolution inductively coupled plasma mass spectrometry.

Origins of variation in lead isotope ratios

Most elements exist in nature as different isotopes, which are atoms of the same proton number that possess the same chemical characteristics but vary in the number of neutrons, thereby giving rise to atoms of different atomic weights. Lead is unusual in that it has a wide range of natural isotopic variation, due to the fact that three of its four stable isotopes (^{206}Pb, ^{207}Pb, and ^{208}Pb) lie at the end of major radioactive decay chains. The chains with their half-life are as follows:

$^{238}\mathrm{U} \rightarrow {}^{206}\mathrm{Pb}\ T_{1/2} = 4.468 \times 10^9$ years
$^{235}\mathrm{U} \rightarrow {}^{207}\mathrm{Pb}\ T_{1/2} = 0.7038 \times 10^9$ years
$^{232}\mathrm{Th} \rightarrow {}^{208}\mathrm{Pb}\ T_{1/2} = 14.01 \times 10^9$ years

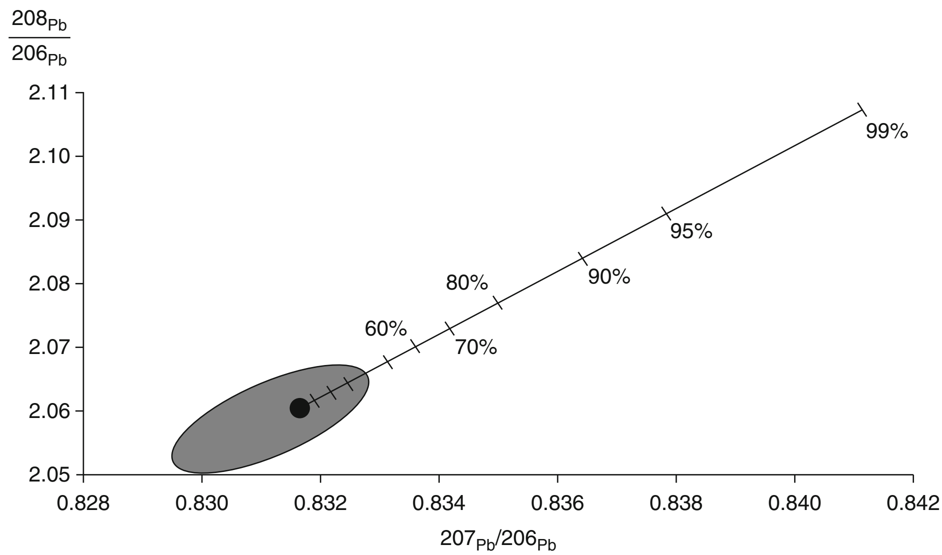
The fourth stable isotope, ^{204}Pb, is not produced by radioactive decay but is residual from the formation of the universe; it is therefore termed *primeval*. By convention, the isotopic composition of lead is discussed in terms of ratios. Geochemists use ^{206}Pb/^{204}Pb, ^{207}Pb/^{204}Pb, and ^{208}Pb/^{204}Pb, since ^{204}Pb is non-radiogenic. These ratios occur in the equations for the isotopic evolution of ore bodies, but there is also a practical reason for using ratios, since ratios can be measured more precisely than the individual abundances using either thermal ionization mass spectrometry (TIMS) or inductively coupled plasma mass spectrometry (ICP-MS).

The lead isotopic composition of an ore body is controlled by the original isotopic composition of the lead at the time of emplacement, the original amount of uranium and thorium in the deposit, and the geological age of the deposit, which means that the isotopic composition of an ore body can be used to indicate the time elapsed since the formation of that body. A number of models exist that can predict the isotopic composition of the ore body, given the starting composition and the age – although many deposits exist for which these models do not give good predictions (Pollard and Heron, 2008, 316). Geologists have been quick to exploit this tool, first to obtain an estimate of the age of the Earth, and subsequently to estimate the geological age of the various metalliferous deposits.

Lead isotope ratio measurements in archaeology

The use of "chemical fingerprinting" to trace metal objects back to their ore source has been one of the main goals of archaeological chemistry since at least the 1930s. Achieving this by chemical analysis is difficult, however, because of the use of high temperature processes causing selective volatilization and the potential effects of mixing and recycling (Bray and Pollard, 2012; Pollard et al., 2014). Brill and Wampler (1967) showed that by using measurements of the lead isotope ratios, it was possible to differentiate lead coming from Laurion in Greece from that obtained from England and Spain. They did note that an ore sample from northeastern Turkey fell into the same "isotope space" as that occupied by three ores from England, thus presaging some of the subsequent interpretational difficulties. The scope of this method was vastly increased when researchers realized that it could be applied not only to metallic lead artifacts (archaeologically rare) but also to the traces of lead left in silver objects extracted from argentiferous lead ores by cupellation (Barnes et al., 1974) and also to the traces of lead in copper objects smelted from impure copper ores (Gale and Stos-Gale, 1982).

The potential issue of lead isotope fractionation during anthropogenic processing was not ignored by the pioneers of the method, since, if it did occur, it might have invalidated the method by changing the isotopic ratios through some separation mechanism. As a test, Barnes et al. (1978) compared the lead isotope ratios of galena (PbS, lead sulfide) with those of (1) the lead smelted from it, (2) litharge (PbO) prepared from the smelted lead, and (3) a K_2O-PbO-SiO_2 glass and a yellow pigment ($Pb_2Sb_2O_7$) prepared from the same lead. They reported no difference in any of the measured ratios, within the precision then available. Hindsight, however, suggests that these experiments may not have been those expected to give the most significant fractionation. Scaife (1993) suggested that non-equilibrium evaporation from a liquid could have a significant effect on the isotopic ratio of lead, providing that the non-equilibrium losses are sufficiently large. He showed (Figure 1) that 40 % non-equilibrium losses would be sufficient to move a sample from the center to the edge of the published lead isotope field for Laurion, and above 60 % would remove it completely



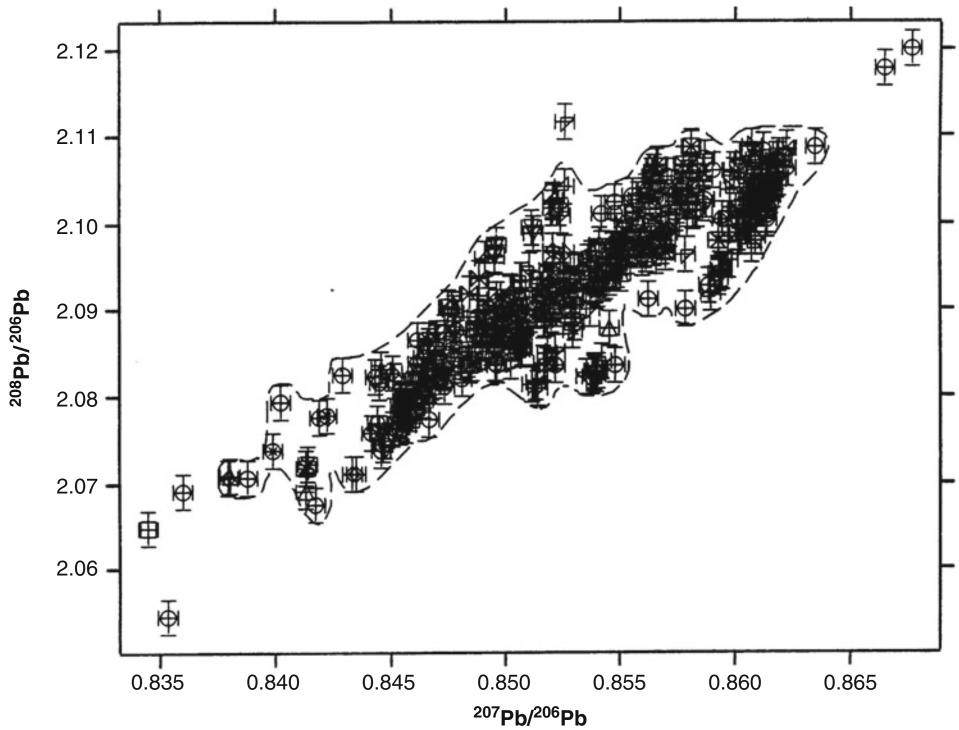
Lead Isotopes, Figure 1 The theoretical effect of non-equilibrium evaporation on the lead isotope ratios of an ore sample from the Laurion field (from Scaife, 1993, Figure 9.3).

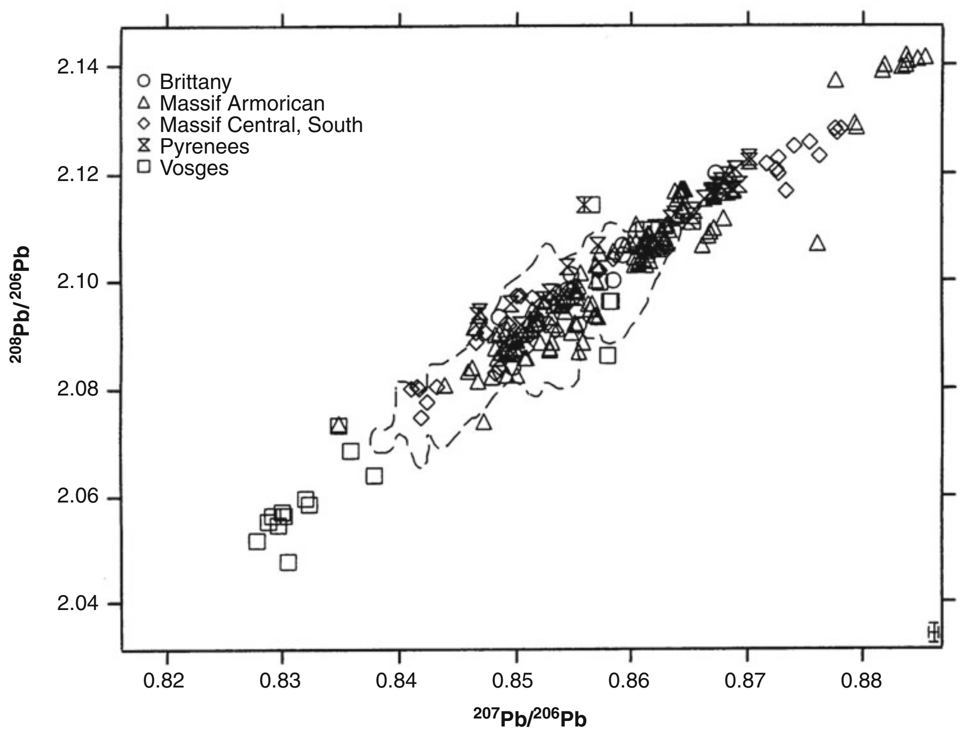
from the field (Pollard and Heron, 2008, 324). The shaded ellipse in Figure 1 represents the typical range of the Laurion field ores for the ratios of the coordinate axes, and the diagonal line indicates progressive deviation as the non-equilibrium loss increases beyond 40 %. In the experiments reported by Barnes et al. (1978), the losses were much lower than this; hence, it is not surprising that no measurable fractionation was observed. Experiments by Pernicka and Bachmann (1983) on the cupellation of silver from Laurion galenas revealed that the process did not result in any fractionation. In the 1990s, a series of simulated laboratory metallurgical processes were carried out, and despite occasionally achieving significant lead losses, isotopic measurements showed no significant change (Budd et al., 1995). More recently, however, Cui and Wu (2011) measured such fractionation using high-resolution ICP-MS but concluded that the magnitude is unlikely to influence provenance studies. Subsequent application of the theory of non-equilibrium evaporation to other metallic systems of archaeological interest, particularly brass (copper-zinc), suggested that the non-equilibrium evaporation model may be appropriate to this system (Budd et al., 1999).

The application of lead isotope measurements in archaeology

The discovery that the isotope ratios of lead vary measurably from metal deposit to metal deposit and are unaffected by anthropogenic processing was naturally hailed as a major breakthrough in the scientific study of archaeological metals. It has been widely applied in studies of ancient metallurgy, particularly in Late Bronze Age metal production in Anatolia and the Eastern Mediterranean. Early enthusiasm soon became tempered by reservations that focused on issues such as the statistical definition of an "ore field" (i.e., how consistent must a set of isotope ratios be to indicate a single metalliferous source) and, given that lead isotope ratio data are not normally distributed, the identification and treatment of "outliers" (Pollard, 2009). A particular case study indicates the degree of caution necessary when trying to use lead isotopes to identify the source of a metal object. In their work on the British sources of copper in the Bronze Age, Rohl and Needham (1998) showed that despite the fact that nonferrous mineralization in the British Isles occurs in four different geological environments, their isotope data revealed no systematic differences among them (Figure 2). In fact, these authors presented the data from all British and Welsh ore sources as EWLIO – the "English and Welsh Lead Isotope Outline." They also explored the relationship between the EWLIO sources and neighboring Scottish, Irish, French, and German ones; in all cases, the data from the neighboring sources overlapped those of the EWLIO, although they often did extend beyond. Particular attributions can sometimes be made (e.g., certain parts of Cornwall have high uranium, which gives a very distinctive lead isotope signature), but it seems clear that, in this case, isotope data are insufficient to characterize uniquely the source of the material. This is an important finding, confirming the generic problem of field overlap first identified by Brill and Wampler (1967). Not all geographically discrete ore fields are isotopically distinct, and therefore, no amount of statistical manipulation can separate groups which fundamentally overlap in the measured parameters.

This difficulty need not be a complete impasse. The "unguided" technique of measuring isotope ratios in an archaeological object and then comparing them to





Lead Isotopes, Figure 2 Scatter plots of lead isotopes ($^{208}Pb/^{206}Pb$ vs. $^{207}Pb/^{206}Pb$): (**a**) "EWLIO" galenas from all English and Welsh lead sources (Rohl and Needham, 1998, 37); (**b**) isotopes from French lead minerals superimposed against EWLIO, showing substantial overlap (Rohl and Needham, 1998, 71) (From Rohl and Needham (1998), with permission. © The Trustees of the British Museum).

a database of potential ore source values in the hope of finding a "match" is largely discredited. This approach would normally be difficult to pursue in any case because much of the raw data on source values remains unpublished. But there is still tremendous value in the technique as a carefully constructed discriminatory test. It is, after all, an axiom of the provenance hypothesis (Wilson and Pollard, 2001) that chemical or isotopic measurements can never *prove* an association with a particular ore source, but they can *disprove* such an association, thereby subjecting an hypothesis to possible rejection. There is thus an increasing tendency to use lead isotope measurements as one of a set of tools (including other isotope systems or elemental analysis) which, when combined with good quality archaeological data, can be used to distinguish between a set of hypotheses relating to human behavior (Pollard and Bray in press).

Advances in analytical instrumentation, and specifically the high-throughput capacity, multi-element sensitivity, and isotopic resolution of the new generation of high-resolution inductively coupled plasma mass spectrometers, mean that capacity is no longer limited by analytical constraints. In particular, with sensitivities for isotopic ratios such as lead comparable to (if not better) that of conventional TIMS instrumentation (Halliday et al., 1998), the widespread use of HR-ICP-MS machines has heralded a new age of relatively rapid and cheap isotopic and chemical studies of archaeological materials. This is happening not only with lead isotopes but also with isotopes of copper (Gale et al., 1999) and tin (Clayton et al., 2002). Recent lead isotope studies of archaeological metals have tended to focus on less well-known areas of the world (archaeometallurgically speaking), such as South Asian metal icons (Srinivasan, 1999), Islamic copper objects (Al-Saad, 2000), bronze Punic coins from Sardinia (Attanasio et al., 2001), Southeast Asian copper sources (Pryce et al., 2011), and also iron artifacts (Degryse et al., 2007). Moreover, lead isotopes have also been used on nonmetallic archaeological materials, such as pottery (Renson et al., 2011), glazed pottery from China (Cui et al., 2010), and painted pottery from New Mexico (Huntley et al., 2007). Nor is the technique limited to inorganic materials. Lead isotopes measured in dental enamel, usually combined with other indicators such as strontium and oxygen isotopes, are now being widely used to "provenance humans" – i.e., to determine where a particular individual was living when her or his dental enamel was being formed (depending on the tooth examined). This offers the potential to reconstruct individual mobility, but also larger archaeological issues such as the migration of groups of people, and also the cultural identity of groups within populations (e.g., Valentine et al., 2008).

Summary

The use of lead isotopes in archaeology, initially as a technique to identify the source of the metal (primarily silver and copper) used for artifacts, but lately on a wider range of material and even human dental enamel, has gone through a typical cycle of enthusiastic adoption followed by a slower reevaluation of the best ways in which to deploy the technique. It is best used in combination with other techniques, and it always requires a careful appraisal of the geological context of the data. It is, together with all scientific applications in archaeology, most effective when used to answer specific, well-constructed archaeological questions rather than as an unguided tool. With the recent developments in essentially nondestructive analysis by laser ablation coupled with ICP-MS, one should look forward to an ever-increasing portfolio of applications.

Bibliography

Al-Saad, Z., 2000. Technology and provenance of a collection of Islamic copper-based objects as found by chemical and lead isotope analysis. *Archaeometry*, **42**(2), 385–397.

Attanasio, D., Bultrini, G., and Ingo, G. M., 2001. The possibility of provenancing a series of bronze Punic coins found at Tharros (western Sardinia), using the literature lead isotope database. *Archaeometry*, **43**(4), 529–547.

Barnes, I. L., Shields, W. R., Murphy, T. J., and Brill, R. H., 1974. Isotopic analysis of Laurion lead ores. In Beck, C. W. (ed.), *Archaeological Chemistry*. Washington, DC: American Chemical Society. Advances in Chemistry Series 138, pp. 1–10.

Barnes, I. L., Gramlich, J. W., Diaz, M. G., and Brill, R. H., 1978. The possible change of lead isotope ratios in the manufacture of pigments: A fractionation experiment. In Carter, G. F. (ed.), *Archaeological Chemistry–II*. Washington, DC: American Chemical Society. ACS Advances in Chemistry Series 171, pp. 273–277.

Bray, P. J., and Pollard, A. M., 2012. A new interpretative approach to the chemistry of copper-alloy objects: source, recycling and technology. *Antiquity*, **86**(333), 853–867.

Brill, R. H., and Wampler, J. M., 1967. Isotope studies of ancient lead. *American Journal of Archaeology*, **71**(1), 63–77.

Budd, P., Pollard, A. M., Scaife, B., and Thomas, R. G., 1995. The possible fractionation of lead isotopes in ancient metallurgical processes. *Archaeometry*, **37**(1), 143–150.

Budd, P., Lythgoe, P., McGill, R. A. R., Pollard, A. M., and Scaife, B., 1999. Zinc isotope fractionation in liquid brass (Cu/Zn) alloy: potential environmental and archaeological applications. In Pollard, A. M. (ed.), *Geoarchaeology: Exploration, Environments, Resources*. London: Geological Society. Geological Society of London Special Publication 165, pp. 147–153.

Clayton, R., Andersson, P., Gale, N. H., Gillis, C., and Whitehouse, M. J., 2002. Precise determination of the isotopic composition of Sn using MC-ICP-MS. *Journal of Analytical Atomic Spectrometry*, **17**(10), 1248–1256.

Cui, J. F., and Wu, X. H., 2011. An experimental investigation on lead isotopic fractionation during metallurgical processes. *Archaeometry*, **53**(1), 205–214.

Cui, J. F., Lei, Y., Jin, Z. B., Huang, B. L., and Wu, X. H., 2010. Lead isotope analysis of Tang sancai pottery glazes from Gongyi kiln, Henan province and Huangbao kiln, Shaanxi province. *Archaeometry*, **52**(4), 597–604.

Degryse, P., Schneider, J., Kellens, N., Waelkens, M., and Muchez, P., 2007. Tracing the resources of iron working at ancient Sagalassos (south-west Turkey): a combined lead and strontium isotope study on iron artefacts and ores. *Archaeometry*, **49**(1), 75–86.

Gale, N. H., and Stos-Gale, Z. A., 1982. Bronze age copper sources in the mediterranean: a new approach. *Science*, **216**(4541), 11–19.

Gale, N. H., Woodhead, A. P., Stos-Gale, Z. A., Walder, A., and Bowen, I., 1999. Natural variations detected in the isotopic composition of copper: possible applications to archaeology and geochemistry. *International Journal of Mass Spectrometry*, **184**(1), 1–9.

Halliday, A. N., Lee, D.-C., Christensen, J. N., Rehkämper, M., Yi, W., Luo, X. Z., Hall, C. M., Ballentine, C. J., Pettke, T., and Stirling, C., 1998. Applications of multiple collector-ICPMS to cosmochemistry, geochemistry, and paleoceanography. *Geochimica et Cosmochimica Acta*, **62**(6), 919–940.

Huntley, D. L., Spielmann, K. A., Habicht-Mauche, J. A., Herhahn, C. L., and Flegal, A. R., 2007. Local recipes or distant commodities? Lead isotope and chemical compositional analysis of glaze paints from the Salinas pueblos, New Mexico. *Journal of Archaeological Science*, **34**(7), 1135–1147.

Pernicka, E., and Bachmann, H. G., 1983. Archäometallurgische Untersuchungen zur antiken Silbergewinnung in Laurion III. Das Verhalten einiger Spurenelemente beim Abtreiben des Bleis. *Erzmetall*, **36**(12), 592–597.

Pollard, A. M., 2009. 'What a long strange trip it's been': lead isotopes in archaeology. In Shortland, A. J., Freestone, I. C., and Rehren, T. (eds.), *From Mine to Microscope: Advances in the Study of Ancient Technology*. Oxford: Oxbow Books, pp. 181–189.

Pollard, A. M., and Heron, C., 2008. *Archaeological Chemistry*, 2nd edn. Cambridge: Royal Society of Chemistry.

Pollard, A. M., Bray, P. J., and Gosden, C., 2014. Is there something missing in scientific provenance studies of prehistoric artefacts? *Antiquity*, **88**(340), 625–631.

Pollard, A. M., and Bray, P. J., 2015. A new method for combining lead isotope and lead abundance data to characterize archaeological copper alloys. *Archaeometry*, **57**(6): 996–1008.

Pryce, T. O., Brauns, M., Chang, N., Pernicka, E., Pollard, A. M., Ramsey, C., Rehren, T., Souksavatdy, V., and Sayavongkhamdy, T., 2011. Geochemical and technological variation in prehistoric Southeast Asian primary copper production. *Journal of Archaeological Science*, **38**(12), 3309–3322.

Renson, V., Coenaerts, J., Nys, K., Mattielli, N., Vanhaecke, F., Fagel, N., and Claeys, P., 2011. Lead isotopic analysis for the identification of Late Bronze Age pottery from Hala Sultan Tekke (Cyprus). *Archaeometry*, **53**(1), 37–57.

Rohl, B., and Needham, S., 1998. *The Circulation of Metal in the British Bronze Age: The Application of Lead Isotope Analysis*. London: British Museum. British Museum Occasional Paper 102.

Scaife, B., 1993. *Lead Isotope Analysis and Archaeological Provenancing*. Unpublished BSc dissertation, Department of Archaeological Sciences, University of Bradford.

Srinivasan, S., 1999. Lead isotope and trace element analysis in the study of over a hundred South Indian metal icons. *Archaeometry*, **41**(1), 91–116.

Valentine, B., Kamenov, G. D., and Krigbaum, J., 2008. Reconstructing Neolithic groups in Sarawak, Malaysia through lead and strontium isotope analysis. *Journal of Archaeological Science*, **35**(6), 1463–1473.

Wilson, L., and Pollard, A. M., 2001. The provenance hypothesis. In Brothwell, D. R., and Pollard, A. M. (eds.), *Handbook of Archaeological Sciences*. Chichester: Wiley, pp. 507–517.

Cross-references

Geochemical Sourcing
Inductively Coupled Plasma-Mass Spectrometry (ICP-MS)
Metals

LIANG BUA

Kira E. Westaway
Department of Environmental Sciences, Macquarie University, North Ryde, NSW, Australia

Definition

Meaning "cool cave" in the local Manggarai dialect, this infamous large limestone cave, 7 km northwest of Ruteng in Western Flores, Indonesia, is renowned for its deeply stratified deposits (17+ m) containing stone artifacts and faunal remains (Morwood et al., 2004), and the discovery of an almost complete skeleton (and parts belonging to several others) of a new species of diminutive human named *Homo floresiensis* (Brown et al., 2004). Flores falls within the area called Wallacea, which represents islands that have never been connected to mainland Southeast Asia on the west and Australia on the east due to the presence of deep trenches that have limited major biotic migrations even during intervals of low Pleistocene sea level.

The large cathedral-like cave of Liang Bua (Figures 1 and 2) is decorated by a dense array of stalactites. It was first excavated by the Dutch priest Father Theodor Verhoeven (1950–1965) revealing a wealth of Neolithic burials with grave goods (Verhoeven, 1953). More extensive excavations followed by R. P. Soejono from 1978 to 1989 (Soejono, 1980, 1985). The full extent of the cave's potential was not revealed until a joint Australian-Indonesian team led by Mike Morwood (2001–2004) extended the west wall excavations using an innovative method of shoring to guard against collapse as lower levels of the cave were explored. These deeper pits exposed the skeletal remains of a mature female of diminutive stature (Morwood et al., 2004, 2005) that was affectionately nicknamed "Hobbit" by the team members. This skeleton represented a species of humans that had a tiny brain and stood only a meter tall with ape-like limb proportions.

Liang Bua formed as a stacked cave system in a tropical karst landscape that evolved rapidly due to the availability of water for solution of the rock and the rapid uplift caused by subduction in a tectonically active region. It was originally formed as a connected, subterranean solution chamber ~600 ka and was later exposed by river downcutting and cave collapse that were fueled by the uplift (Westaway et al., 2009a). Presently, the site is situated at the same elevation as the highest of three alluvial terraces (510 m amsl), which were deposited by the Wae Racang River in a wide Miocene limestone valley. The subaerial exposure of Liang Bua by the downcutting river left its mark at the rear of the cave with a high-energy conglomerate deposit that fines upwards (Westaway et al., 2007). This exposure event, dated at 190 ka, created the first opportunity for human occupation, and since then, the

Liang Bua, Figure 1 Photograph looking to the northwest at the front of Liang Bua. The excavations are visible in the *bottom right* with the large spoil heap in the background. Note the profusion of stalactites on the cave roof that feed the large stalagmite block in the *center* and the extensive flowstones that coat the west wall. The *Homo floresiensis* skeleton was discovered in Sector VII in the *bottom right* of the photograph. The cave was formed when the rear rounded chamber coalesced with the domed front chamber from 600 ka and was later exposed ~190 ka.

cave has accumulated a wealth of archaeological material during an ~100 ka occupation period. The ages of the three alluvial terraces, dated by red TL techniques, at 118 ± 48, 18 ± 4, and 5 ± 2 ka (Westaway et al., 2009a) illustrate when the river occupied that elevation and thus provide a proxy for alluvial downcutting. The combined rate of 305 mm/ka is much faster than the rate of cave development (113 mm/ka) (Westaway et al., 2010) estimated using assumptions of karstification rates (the height of the highest cave above sea level and the age of the limestone), but both are slower than the rate of uplift (500 mm/ka) according to the elevated marine terraces in nearby Sumba Island (Bard et al., 1996). This suggests that the landscape evolution in this region displays some lag effects when responding to uplift but that the fluvial system, despite having a large proportion of its water volume channeled underground, responds much quicker than cave development (Westaway et al., 2010). This information provides a useful context for the formation and sedimentary context of the site.

From 600 ka to the present, a series of geomorphic events influenced the structure of the cave and deposits, creating a complex stratigraphy containing stone artifacts, plant and animal remains, pottery, metal items, and human skeletal remains. Within these deposits, nine main sedimentary units have been identified, and the stratigraphic relationships between these units provide the evidence needed to reconstruct the geomorphic history of the cave. This history was dominated by water action, including slope wash processes, channel formation, pooling of water, and flowstone precipitation, which created waterfalls, cut-and-fill stratigraphy, large pools of water, and extensive flowstone cappings. The sequence of geomorphological events – exposure of cave and high-energy deposition, suspension in a pool, creation of higher ground, channel erosion, cut and fill, bank and pool deposition, volcanic events, and sheetwash – restricted occupation to certain zones. Continuous occupation of the cave may not have been possible until after ~100 ka, when the accumulated water had drained from the front chamber. The next ~89 ka were dominated by flowing water creating waterfalls, cut-and-fill by channels, periodic pooling of water, occasional volcanic events, and the creation of a dominant zone of occupation – established ~74–61 ka in the center of the cave. This evidence was protected from sheetwash and channel processes by an extensive flowstone that caps this occupation zone (Westaway et al., 2009b).

Since 2004, the new species interpretation has been criticized by claims that the fossils represent modern

Liang Bua, Figure 2 Photograph of the rear of Liang Bua taken from the northwest corner looking southeast. The height of the cave and shape of the domed front chamber are apparent, along with the conglomerate deposit on the *right* that represents the river's first violent exposure of the once subterranean chamber. Excavations have been conducted mostly on the flat *front* section of the cave where the evidence for occupation was concentrated.

humans with pathological abnormalities (e.g., Jacob et al., 2006; Henneberg and Schofield, 2008). However, the team argues that the fossils were securely discovered within the unbroken 100 kyr record of sediments within the cave, and that they were associated with a stone tool technology (Moore et al., 2009), complex faunal assemblages that reveal cut marks (van den Bergh et al., 2009), living floors with sharp stone tools and hearths (van den Bergh et al., 2009), and an often harsh environment both inside and outside the cave (Westaway et al., 2009a, c) that influenced their pattern of occupation (Westaway et al., 2009c). The skeletal material can be dated within the interval of 95–18 ka, and stone tools are as old as 190 ka (although age ranges are currently being revised). This evidence, which also informs about paleoclimate changes, insular evolutionary processes, human dispersal, and the arrival of new peoples, animals, and technologies, suggests that there is more to learn about Liang Bua than merely the presence of *H. floresiensis* (Morwood et al., 2009). This context was reconstructed using a barrage of dating techniques: radiocarbon, luminescence (OSL and red TL), U-series, and ESR (Roberts et al., 2009).

The cave has not yet revealed all of it secrets. The current Liang Bua excavations started in 2001 by Mike Morwood are ongoing by his team, with 28 large pits now excavated to 11+ m. This new evidence is providing a better understanding of the complex stratigraphy and its association with the archaeological material so that a more detailed chronological framework has been established that will form the basis of publications in the near future.

Bibliography

Bard, E., Jouannic, C., Hamelin, B., Pirazzoli, P. A., Arnold, M., Faure, G., Sumosusastro, P., and Syaefudin, 1996. Pleistocene sea levels and tectonic uplift based on dating of corals from Sumba Island, Indonesia. *Geophysical Research Letters*, **23**(12), 1473–1476.

Brown, P., Sutikna, T., Morwood, M. J., Soejono, R. P., Jatmiko, Saptomo, E. W., and Due, R. A., 2004. A new small-bodied hominin from the Late Pleistocene of Flores, Indonesia. *Nature*, **431**(7012), 1055–1061.

Henneberg, M., and Schofield, J., 2008. *The Hobbit Trap*. Kent Town: Wakefield Press.

Jacob, T., Indriati, E., Soejono, R. P., Hsü, K., Frayer, D. W., Eckhardt, R. B., Kuperavage, A. J., Thorne, A., and Henneberg, M., 2006. Pygmoid Australomelanesian *Homo sapiens* skeletal remains from Liang Bua, Flores: population affinities and pathological abnormalities. *Proceeding of the National Academy of Science*, **103**(36), 13421–13426.

Moore, M. W., Sutikna, T., Jatmiko, T., Morwood, M. J., and Brumm, A., 2009. Continuities in stone flaking technology at Liang Bua, Flores, Indonesia. *Journal of Human Evolution*, **57**(5), 503–526.

Morwood, M. J., Soejono, R. P., Roberts, R. G., Sutikna, T., Turney, C. S. M., Westaway, K. E., Rink, W. J., Zhao, J.-x., van den Bergh, G. D., Due, R. A., Hobbs, D. R., Moore, M. W., Bird, M. I., and Fifield, L. K., 2004. Archaeology and age of a new hominin from Flores in eastern Indonesia. *Nature*, **431**(7012), 1087–1091.

Morwood, M. J., Brown, P., Jatmiko, Sutikna, T., Saptomo, E. W., Westaway, K. E., Due, R. A., Roberts, R. G., Maeda, T., Wasisto, S., and Djubiantono, T., 2005. Further evidence for small-bodied hominins from the Late Pleistocene of Flores, Indonesia. *Nature*, **437**(7061), 1012–1017.

Morwood, M. J., Sutikna, T., Saptomo, E. W., Jatmiko, E. W., Hobbs, D. R., and Westaway, K. E., 2009. Preface: research at Liang Bua, Flores, Indonesia. *Journal of Human Evolution*, **57**(5), 437–449.

Roberts, R. G., Westaway, K. E., Zhao, J.-x., Turney, C. S. M., Bird, M. I., Rink, W. J., and Fifield, L. K., 2009. Geochronology of cave deposits at Liang Bua and of adjacent river terraces in the Wae Racang valley, western Flores, Indonesia: a synthesis of age estimates for the type locality of *Homo floresiensis. Journal of Human Evolution*, **57**(5), 484–502.

Soejono, R. P., 1980. *Laporan penelitian arkeologi di Liang Bua, Tahun 1978 dan 1980*. Unpublished report. Jakarta: Indonesian National Research Centre of Archaeology.

Soejono, R. P., 1985. *Laporan penelitian arkeologi di Liang Bua, Tahun 1985*. Unpublished report. Jakarta: Indonesian National Research Centre of Archaeology.

Van den Bergh, G. D., Meijer, H. J. M., Awe, R. D., Morwood, M. J., Szabó, K., van den Hoek Ostende, L. W., Sutikna, T., Saptomo, E. W., Piper, P. J., and Dobney, K. M., 2009. The Liang Bua faunal remains: a 95 k.yr. sequence from Flores, East-Indonesia. *Journal of Human Evolution*, **57**(5), 527–537.

Verhoeven, T., 1953. Eine Mikrolithenkultur in Mittel- und West-Flores. *Anthropos*, **48**(3–4), 597–612.

Westaway, K. E., Morwood, M. J., Roberts, R. G., Zhao, J.-x., Sutikna, T., Saptomo, E. W., and Rink, W. J., 2007. Establishing the time of initial human occupation of Liang Bua, western Flores, Indonesia. *Quaternary Geochronology*, **2**(1–4), 337–343.

Westaway, K. E., Roberts, R. G., Sutikna, T., Morwood, M. J., Drysdale, R., Zhao, J.-x., and Chivas, A. R., 2009a. The evolving landscape and climate of western Flores: an environmental context for the archaeological site of Liang Bua. *Journal of Human Evolution*, **57**(5), 450–464.

Westaway, K. E., Sutikna, T., Saptomo, W. E., Jatmiko, Morwood, M. J., Roberts, R. G., and Hobbs, D. R., 2009b. Reconstructing the geomorphic history of Liang Bua, Flores, Indonesia: a stratigraphic interpretation of the occupational environment. *Journal of Human Evolution*, **57**(5), 465–483.

Westaway, K. E., Morwood, M. J., Sutikna, T., Moore, M. W., Rokus, A. D., van den Bergh, G. D., Roberts, R. G., and Saptomo, E. W., 2009c. *Homo floresiensis* and the Late Pleistocene environments of eastern Indonesia: defining the nature of the relationship. *Quaternary Science Reviews*, **28**(25–26), 2897–2912.

Westaway, K. E., Sutikna, T., Morwood, M. J., and Zhao, J.-x., 2010. Establishing rates of karst landscape evolution in the tropics: a context for the formation of archaeological sites in western Flores, Indonesia. *Journal of Quaternary Science*, **25**(6), 1018–1037.

Cross-references

Alluvial Settings
Cave Settings
Radiocarbon Dating
U-Series Dating

LITHICS

M. Steven Shackley
Geoarchaeological XRF Laboratory, Department of Anthropology, University of California, Berkeley, CA, USA

Synonyms

Archaeological stone in geoarchaeology; Archaeometry of stone; Lithic technology; Petrology of lithics

Definition

Lithics. Stone used and modified in prehistory. The analytical tools and methods used to understand lithics in the past.

Introduction

Lithics is the term used to describe stone implements of the past and their study. It includes analysis of archaeologically recovered tools as well as the processes used to manufacture them based on empirical examination of residual evidence, experimentation, and analogy to modern and historic toolmaking societies. Lithic technologists work directly with the stone artifacts themselves and are concerned with the above goals. In contrast, this entry deals with the geoarchaeological aspects of lithic analysis, i.e., the information obtained by earth science techniques such as petrology, that further help refine our understanding of tool-using behavior. The entry will also examine some of the history and advances made in geoarchaeological approaches, with special emphasis on the directions that twenty-first century geoarchaeology and archaeometry are currently taking toward an understanding of the composition of stone artifacts. From chipped stone to sculptural stone, using both optical methods (petrography) and analytical chemistry, the quantity and quality of research have been increasing exponentially. No attempt will be made here to describe chronometric techniques applied to stone. The present entry reexamines to some extent two previous reviews (Shackley, 1998a, 2008), but the subject is covered by a huge literature that is well beyond the focus of the limited treatment here—for example, see Delage (2003) for chert and Shackley (2008) for an extensive bibliography.

In 1983, D. R. C. Kempe and Anthony Harvey published an edited volume entitled *The Petrology of Archaeological Artefacts*. This book was the first attempt to compile the ever-increasing work on the geoarchaeological analysis of stone in all its forms, from chipped to sculptural stone, and it included chapters on ceramics and metals. This landmark study received very little attention by lithic technologists, particularly in the Americas, yet lithic technologists have much to gain from instrumental analyses of stone, and many have recently come to see the value of a geoarchaeological perspective

(Shackley, 1998a, 2008 Odell, 2003; Högberg and Olausson, 2007; Hughes et al., 2012).

The goal of this entry is to address some of the important recent advances as well as the continuing problems that affect geochemical studies of archaeologically recovered stone implements; this is done with the archaeologist in mind rather than the trained geochemist. Important new and experimental techniques in archaeometry, both in the field and lab, are being applied to stone tools and structural stone studies in archaeology. Not all emerging possibilities can be covered – for example, isotope studies through ICP-MS (Speakman and Neff, 2005) – an emphasis will be placed on problems of chert and obsidian characterization.

The chemical characterization of stone

The writer has written frequently about a "sourcing myth" in archaeometry (Shackley, 1998a, 2005). Archaeometrists involved in chemical characterization know very well the physical and geochemical foundations of the varied techniques that have been used to identify elemental composition in many kinds of stone artifact: x-ray fluorescence (XRF), neutron activation analysis (NAA), proton-induced x-ray emission/proton-induced gamma ray emission spectrometry (PIXE/PIGME), mass spectrometry (MS), inductively coupled plasma-mass spectrometry (ICP-MS), and others (see Speakman and Shackley, 2012). Archaeologists are not always so familiar with these methods, and they are not always aware of issues involving statistical probability and its role in assigning an artifact to a source (see Baxter, 1994; Neff and Glascock, 1995; Shackley, 1998b). The success of any attempt to use geochemical composition to locate the raw materials employed in artifact manufacture will depend heavily upon unimpeded communication between the scientist and archaeologist, a situation that should, but does not always, occur. Furthermore, the conclusions of an archaeometrist can rarely be directly checked by the archaeologist, who must therefore trust the results. This places much weight on the accuracy of the science, but it also suggests that archaeologists should not use such data alone to support their conclusions. The geochemical data should be one part of a search for multiple lines of evidence. This review will survey problems in the chemical characterization of two very important substances used throughout prehistory and which have become a focus for much archaeometric research in the last three decades: (1) secondary siliceous sediments, here collectively called chert, and (2) volcanic glass, both silicic and mafic. The issues raised are typical of the analysis of other stone materials, particularly those that are heterogeneous.

Returning to the "sourcing myth," the term "sourcing" has become one of the most misused terms in archaeometry. Archaeologists and geoarchaeologists use it often, and most understand the word to mean that specimens submitted for analysis will return with a certified provenance that is not probabilistic at all, but confidently determined. In truth, nothing is ever really "sourced." The best outcome is a chemical characterization and a probable fit of the artifact's resultant profile to similar profiles obtained from raw material obtained at a known source. The key word here is *known*. Many regions of the world are poorly covered with respect to source data, and matches can be obtained only when source materials that might have been used for artifact production have been analyzed and their spectra already archived. Thus, one can never really be sure using geochemical data alone that an artifact's material came from a particular source, even beyond the scientific process of orderly refutation of alternatives (Ward, 1977; Luedtke, 1992; Hughes and Smith, 1993; Williams-Thorpe, 1995; Cauvin and Balkan-Atlı, 1996; Gratuze, 1999; Kuzmin et al., 2002; Shackley, 2005).

Chert and characterization

Attempts to determine the provenance of chert through chemical characterization have proven to be difficult and vexing to archaeologists and archaeometrists for decades (Luedtke and Myers, 1984; Matiskainen et al., 1989; Luedtke, 1992; Warashina, 1992; Church, 1995; Hoard et al., 1995; Roll et al., 2005; Högberg and Olausson, 2007; Hughes et al., 2012). This is due mainly to the processes of chert formation, which involve precipitation from a parent material at ambient temperatures where only certain elements and compounds can be removed from the original matrix to become part of the chert body. Additionally, sources of chert, particularly Phanerozoic marine cherts, are by their very nature often broadly distributed, covering large geographic expanses; the extent of their uniformity and wide dispersion decreases the possibility of discriminating local varieties and therefore diminishes their utility as a means to derive inferences for exchange, interaction, or procurement processes. Most of the techniques that have proven helpful in deriving useful chemical data for cherts are destructive and expensive, further limiting their attractiveness for routine analysis, especially where conservation of objects is an issue (see Roll et al., 2005). Barbara Luedtke's (1992) treatment of the subject for archaeologists is an excellent summary. Among many useful ideas, Luedtke suggests a four-step process for determining the probable source of cherts (1992: Appendix A). Her steps have been modified here by the addition of a few more based on this writer's experience. In general, these steps are appropriate for most stone provenance studies.

1. Several similar chemical profiles indicating unknown sources may be detected in stone artifacts from various archaeological contexts. Often these will cluster into groups that compare favorably to raw material from various geologic regions.
2. One should consult the regional geologic literature to ascertain the location of the nearest and most likely rock bodies. (In the case of obsidian, however, volcanic

glass is rarely mentioned in association with mapped rhyolite bodies in the geologic literature.)

3. Frequently, local residents, archaeologists, rock hounds (amateur geologists), rock hound guides, and generally word-of-mouth can provide excellent information when searching for natural sources of obsidian and chert. Nearly all of the obsidian and chert sources "discovered" in the North American Southwest were first found by nonscientists (Shackley, 2005).
4. It is often necessary to begin the search downstream from a probable source area. Many sources formed during the Tertiary Period and earlier have been highly eroded, releasing many nodules and fragments into the sediment load to be carried hundreds of kilometers downstream from their origin (Shackley, 1998c, 2005, 2013).
5. In the field, when a source is discovered, the extent and density of the natural distribution of raw material, its general geologic setting, and the variability of human lithic production in the region should be recorded. Pedestrian transects across the source area should lead to collection of specimens from various sample strata. These specimens will form the basis for optical and/or instrumental analysis, insuring as representative a sample as possible.
6. Determine which techniques or procedures are optimal. For museum specimens, it is often unacceptable to cut thin sections for petrographic analysis or subject them to destructive NAA; in these situations, nondestructive methods like XRF may be acceptable (see Hughes et al., 2012). Each method has its advantages and limitations, and the results of a given technique may not be specifically valid in certain situations (see Goffer, 1980; Neff and Glascock, 1995; Green, 1998; Shackley, 1998a; Roll et al., 2005; Speakman and Neff, 2005).
7. Matching artifactual profiles to those of the sources is the final step. The literature contains many examples of incorrect applications at this stage of the analysis. Multivariate statistical techniques are often sought after, but archaeologists often don't have the quantitative background to evaluate these results. Simple bivariate plots and central tendency statistics that compare the artifacts and geologic data are often sufficient to link artifacts to sources (Hughes, 1984a; Shackley, 1988, 2005; Baxter, 1992; Baxter, 1994; Neff and Glascock, 1995; Glascock et al., 1998).
8. Source descriptions should include exact locations, preferably UTM geographical coordinates, a description of the geologic context, megascopic attributes of the raw stone (cortical and interior variation, nodule size, color, fabric, opacity), distribution of secondary deposits, density and character of lithic reduction (tool production waste, or debitage) at the source, and relevant published sources.

Within the last two decades, archaeometrists and archaeologists have together begun to focus on the problems of chert characterization and source assignment (Church, 1995; Hoard et al., 1995; Roll et al., 2005; Hughes et al., 2012). As archaeologists gain a better understanding of the instrumental techniques involved and the assumptions archaeometrists often must make, they are following appropriate sampling design and presentation of results. Sampling is an important matter, illustrated by the exchange between Church and Hoard et al. cited above. Church rightly questioned whether sampling reduction debris at the source was sufficient and necessary to capture sufficient variability within the raw material. Hoard et al. noted that while some geologic samples were gathered during their work, much of the characterization conducted by their project was based on secondhand collections. Without a firm knowledge of potential chert sources in a region, errors of misassignment will occur, as the level of macroscopic and chemical variability inherent in secondary siliceous sediments can be high. In this case, the potential for sampling error, due mainly to retooling at the source, was great—and potentially unknown to the archaeologist or the archaeometrist (Thomas, 1986, pp. 213–217; Bernard, 2006). Given all these caveats, however, chert characterization and source assignment provide a significant tool in archaeology for understanding lithic production and use. Despite the difficulties of source heterogeneity and the general need to apply destructive or partially destructive techniques, confocal microscopy tied to optical petrography, in addition to the instrumental techniques mentioned here, promises to reveal new data about chert exploitation in the past.

Obsidian characterization and the "Sourcing Myth"

Many of the points outlined for chert studies are equally relevant for obsidian studies in archaeology, but because these homogeneous, disordered, silicic glasses can be so precisely characterized, the potential abuses are much greater. Since it is a common aspect of archaeological practice and a good example for other data sets, a few words will be directed toward some of the problems in the chemical characterization of silicic glasses that directly impact the resolution of archaeological problems.

Obsidian studies in archaeology are a relatively recent aspect of archaeological research (Boyer and Robinson, 1956; Green, 1962; Cann and Renfrew, 1964; Jack and Heizer, 1968; Jack and Carmichael, 1969; Williams-Thorpe, 1995; Green, 1998; Shackley, 2005). Early studies relied on naked eye observation, density measures, and mass spectrometry in an attempt to define source groups and correlate artifacts to sources. The results were mixed. In the late 1960s and early 1970s, with the evolution of relatively inexpensive x-ray fluorescence spectrometers and increasing use of NAA, obsidian studies in archaeology began to be applied in the exploration of exchange and interaction (Glascock, 1994; Shackley, 1998b, 2005; Glascock et al., 2007; Glascock, 2011). Archaeologists working in the Mediterranean, the New

World, and Oceania were particularly keen to exploit these new methods, mainly since the instruments were available at most university campuses (Hughes, 1984b; Nelson, 1984; Shackley, 1988; Tykot, 1992; Shackley, 1995, 2005; Williams-Thorpe, 1995; Green, 1998; Glascock, 2011). By the 1980s, archaeologists in every part of the world where obsidian was naturally present were engaged in obsidian provenance studies. Now thousands, if not tens of thousands, of pieces of archaeological obsidian are analyzed yearly by x-ray fluorescence spectrometry (XRF), neutron activation analysis (NAA or INAA), inductively coupled plasma-mass spectrometry (ICP-MS), and proton-induced x-ray emission-proton-induced gamma ray emission (PIXE/PIGME), and much of this analysis is performed by archaeologists rather than physical scientists (Shackley, 2002). The expanding investigation is a welcome sign, but as discussed above, there is still some concern that many factors affecting accurate source assignment (such as quality of the instrumental results and extent of data from potential sources) will be downplayed in favor of easily derived quantitative estimates.

The obsidian hydration controversy

Obsidian hydration dating has fascinated and frustrated archaeologists for decades (Layton, 1973; Ericson and Kimberlin, 1977; Michels et al., 1983; Stevenson et al., 1987, 1989; Liritzis, 2006). The technique involves measuring the thickness of a veneer of hydration caused when a freshly exposed surface of obsidian absorbs water from the environment. This rim or rind can be seen in thin section, and its thickness has been associated with the length of time since the exposure (due to purposeful flaking in the process of toolmaking) occurred. Obsidian hydration dating hasn't played a major role in Old World chronology building for a number of reasons, and European scholars have not dealt with the controversy in a major way. It is employed mostly in the New World, principally in parts of North America (California, the Great Basin) and Oceania (particularly New Zealand). The historical reasons for this include primarily the dominance of obsidian in those regions and the absence of other datable materials. Currently, many feel it is fraught with too many issues to function as a reliable member of the chronometric tool kit (Shackley, 2005).

Beginning with Friedman and Smith (1960) on dating using obsidian hydration, scholars have moved into two camps: those who believe fervently in the utility and validity of the method (Jackson, 1984; Hall and Jackson, 1989; Hull, 2001; Hull, 2002) and those who find the recurring problems simply too difficult to overcome (Ridings, 1996; Stevenson et al., 1998; Anovitz et al., 1999; Loyd, 2002). Even those who are dubious about the use of obsidian hydration as a direct dating method still work toward the resolution of the problems. Factors that frustrate attempts to use hydration as a direct chronometric method include (1) variances in atmospheric heat and humidity through time; (2) the inability to control for the burial history of the artifact; (3) resetting of the hydration rim after postdepositional burning; (4) seemingly exponential, nonlinear shifts in the absorption of water over time; and (5) inter-observer measurement error. More recently, Hull (2001) has argued that such critiques have emerged simply because researchers focus on the method as a direct rather than relative technique, although Hull seems to use it as the former in her own work (Hull, 2002). A recent symposium exploring the effects of fire on obsidian hydration in California found through empirical observation and experimentation that hydration rims can be reset during forest fire conditions, thereby dealing a lethal blow to the chronometric dimension, at least for the nonbelievers (Deal, 2002; Loyd, 2002; Loyd et al., 2002; Skinner, 2002). Some western federal archaeologists in North America will no longer pay for obsidian hydration analyses through federal funds (Skinner, 2002, and personal communication). Parenthetically, it has been determined through experimentation and field studies that there is no statistically significant change in trace element chemistry when obsidians are heated to high temperatures (Skinner et al., 1997; Shackley and Dillian, 2002; Steffen, 2002).

So, what should archaeologists do? Hull suggests that obsidian hydration should not be seen as a direct chronometric dating method like dendrochronology, but as a relative dating tool to be used within single site contexts where the depositional history and environment are similar from one area to another (2001, p. 1026). In recent, historic period sites, Hull was able to obtain interesting relative dates (with substantial error rates due to the vagaries of hydration) where ^{14}C dating is useless given the inherent uncertainty of the calibration curve in near "modern" periods (see also Ambrose, 1998; Hull, 2002). Though Ridings (1996) and Anovitz et al. (1999) seem willing to claim obsidian hydration a failure, some, including Anovitz, are willing to continue experimentation with the goal of resolving the issues (Friedman et al., 1997; Stevenson et al., 1998).

Instrumentation: which instrument is best?

A frequently asked question concerns which instrument is the best for analyzing stone objects. The answer depends upon the problem design of a given project and the level of precision needed to address that design. Ten years ago, the question was easier to address (Shackley, 1998b), but with the general improvements in technology, instrumental applications in archaeological geochemistry have similarly improved. Almost all instrumental and empirical techniques have been used, including density, magnetism, atomic absorption, PIXE-PIGME, ICP (for obsidian, see Tykot and Young, 1995; Speakman and Neff, 2005; Shackley, 2005), megascopic criteria, and others. Today, three major instrumental methods dominate the field: (1) neutron activation analysis (NAA or INAA), (2) wavelength and energy-dispersive x-ray fluorescence (XRF) including portable XRF (PXRF), and

(3) increasingly, laser ablation inductively coupled plasma-mass spectrometry (LA-ICP-MS) (Neff and Glascock, 1995; Glascock et al., 2005; Shackley, 2005; Speakman and Neff, 2005; Glascock, 2011). All of these methods have benefited from the revolution in microprocessors and the attendant software improvements and are now easier to use (and hence misuse). For archaeologists, Goffer (1980) and, to a certain extent, Harbottle (1982) detail some of the intricacies of each method for an earlier period. Glascock (1991, 2011) presents a good, though technical, treatment of NAA (see also Neff and Glascock, 1995; and see Speakman and Glascock, 2007, which represents a special issue on NAA in *Archaeometry*), and XRF and PIXE-PIGME are explained in some detail in (Shackley, 1998b; Shackley, 2011; see also What Is XRF? http://www.swxrflab.net/xrfinstrument.htm). The present entry will address the relative merits of the three most commonly used analytical techniques – NAA, EDXRF, and PIXE-PIGME—given the real situations encountered by archaeologists.

A level of mythology has also grown regarding the optimal analytic instrument for geochemical studies of stone. The prevailing ideal seems to be that NAA offers the "best" technique if funding is available. For most elements, NAA is precise, and it can detect more elements than the other two methods (Glascock, 1991; Neff and Glascock, 1995; Speakman and Glascock, 2007; Glascock, 2011). Neutron activation analysis, however, has two primary shortcomings. First, it is in essence a destructive technique; while the material is not literally destroyed, depending on the specimen's original size, it may be broken into relatively small pieces, and the analyzed material can remain radioactive for decades. Second, NAA is not readily available, partly due to its elevated cost and partly due to the public fear of nuclear energy. Also, when applied to obsidian characterization, NAA cannot analyze for Sr, Y, Zr, and Ba as accurately as the other two methods (see Shackley, 2005; Craig et al., 2007; Glascock, 2011). These are important incompatible elements in silicic melts and can be extremely valuable in separating sources or dealing with intra-source issues (Hildreth, 1981; Mahood and Hildreth, 1983; MacDonald et al., 1987; Hughes and Smith, 1993). Neutron activation can, however, quite accurately analyze for other incompatibles and rare earth elements that are outside the range of XRF.

For museum specimens and artifacts that are subject to repatriation, NAA is not an appropriate choice. If precision and accuracy are necessary, which can be an issue in intra-source studies and in situations where long-distance exchange is probable, then NAA will always provide the most efficient alternative. Additionally, if the sample is extremely small (<2–5 mm as the largest diameter), NAA or LA-ICP-MS may be the best analytical method. Other methods may require a minimum sample size for optimal results (Davis et al., 2011).

Recently, Michael Glascock compared the results of both NAA and EDXRF analyses of central Mexican obsidian (2011). He concluded: "In most cases, XRF should be sufficient to determine the provenance of the artifacts. However, if the artifacts come from a source that overlap on elements measured by XRF, then short-NAA and long-NAA are a possible way of obtaining the data critical to sourcing these difficult artifacts" (Glascock, 2011, p. 191).

What this means for an archaeologist is that any laboratory employing EDXRF, WDXRF, NAA, PIXE-PIGME, or ICP-MS will provide valid and comparable results, given a sufficient sample size, particularly for obsidian. The constraints for the particular project determine the main criteria for the selection of analytical methods. A more critical factor is likely to be the accuracy and inclusiveness of source data: if the region of interest has not received the level of geoprospection necessary for accurate source assignment, the precision of the instrument employed will not overcome this deficit.

Sampling: how much is enough?

Sampling is not new to archaeology. Over 20 years ago, the US Department of the Interior spent a considerable sum investigating the subject both for confidence in predictive modeling and regional and intra-site sampling (Judge and Sebastian, 1988). Throughout this work, and many other investigations like it, lies the basic tenet of probability theory regarding the simple law of large numbers: as sample size increases, the probability of obtaining a representative sample increases. Given that funding constrains archaeology in all its forms, the law of large numbers is an ever-present demon since collecting an optimal sample is invariably costly. Sampling still deserves consideration at all levels of archaeometric analysis, both in the field and the laboratory; while most projects may not be able to support extensive sampling based on these precepts, the risks inherent in such decisions must be recognized in formulating conclusions. When sampling raw material at source localities as well as artifacts from an archaeological assemblage, there appears to be a minimum number of samples necessary to derive a confident conclusion. The following examples at both the source and artifact assemblage levels are illustrative.

The Mule Creek regional source: "Real" chemical source variability

A 1988 study of the Mule Creek source in western New Mexico sampled 15 obsidian source standards from a population of 200 gathered at five localities. Two chemical "outliers" were noted among the analyzed specimens that showed significantly higher rubidium concentration values (Shackley, 1988, p. 767). These outliers have now been identified as a distinct chemical group, often mixed together with three other chemical groups in the regional Gila Conglomerate (see Shackley, 1995, 2005). The eruptive geology in the area is complex and has been studied by Ratté and others—see Ratté (2004) for a summary of research. For three of these chemical groups, primary in situ localities have been found with natural exposures of perlite (hydrated obsidian) and remnant marekanites (rounded nodules of obsidian eroded from their perlite matrix).

At least four discrete chemical groups were evident, distinguished by their Rb, Y, Nb, and Ba, and to a lesser extent Sr and Zr concentration values; each was named after the localities where marekanites have been found in perlitic lava: Antelope Creek, Mule Mountains, and Mule Creek/North Sawmill Creek, all in New Mexico (Shackley, 1998c, 2005). During the 1994 field season, a fourth subgroup was discovered in Quaternary secondary deposits in the San Francisco River alluvium near Clifton, Arizona. While in situ nodules (marekanites) have not yet been found, they are certainly located somewhere west of the Blue River and north and west of the San Francisco River since none of this "low zirconium" subgroup was discovered in alluvium upstream from the juncture of the Blue and San Francisco Rivers. The genetic relationship is apparent in bivariate and trivariate data plots (Shackley, 2005), signifying that Mule Creek silicic geology possesses a very complex nature that further complicates the subsequent depositional mixing in the Gila River conglomerate. The original random sample of 15 marekanite nodules merely indicated that some variability existed, and only after extensive transect survey and sampling, and the discovery of three localities with marekanites did it become apparent that there was significant chemical variability inherent in the "source." The most important point of this case study is that without the knowledge of these other sub-sources, analysis of archaeologically recovered obsidian artifacts from the region could have promulgated the existence of a new and unknown source.

So, how much should be sampled? It depends on many factors. Often, laboratory analysis will detect variability in archaeological specimens despite the fact that source standards have not demonstrated such variability (Hughes, 1994; Glascock et al., 1998). In some cases, even ten samples sent to an analyst might not be sufficient to define with confidence the high elemental variability of a source. The following source sampling strategy can serve as a guide. It has been compiled based upon research in the American Southwest (Shackley, 1988, 1995, 2005), in Mesoamerica (Glascock, 1994, 2011, Glascock et al., 1998), in the American Northwest (Skinner, 1983), in California and the Great Basin (Hughes, 1984b, 1994; Jackson, 1986, 1989; Hughes and Smith, 1993), in Oceania (Torrence, 1992; Green, 1998; Summerhayes et al., 1998), and in the Mediterranean and the Near East (Williams-Thorpe, 1995; Tykot, 1998; Carter et al. 2006).

1. On-the-ground sample surveys must incorporate the entire primary and secondary extent of the source. This often requires days or weeks of field reconnaissance and extensive discussions with geologists and local inhabitants of the source area.
2. In order to determine the probable location of primary sources, it is often useful to conduct extensive sampling of the secondary distribution; this can isolate probable areas for further study. The San Francisco River alluvial samples were delimited in this way (see above).
3. Mark the location of all samples geographically at least to the section, square kilometer, UTM, or other appropriate global positioning system (GPS) coordinates.
4. Divide the total survey area into sample strata based on the field localities that were collected, and analyze preferably at least five or more samples from *each locality*. "Five or more" does not constitute a magic number that will be appropriate to the variability of every source area.

In some instances, particularly with Quaternary sources, erosion and secondary deposition of primary obsidian may not be an issue since there has been little geologic time for the glass to weather and disperse into the environment; also, large-scale pyroclastic eruptive events may not have occurred during such a short interval (see Shackley, 2005). While this minimizes the problems of secondary deposition, it does not mitigate the challenges of possible intra-source chemical variability.

Archaeometry and the inference of tool use

Most of the history of prehistoric lithic technology studies have been dominated by direct observation, experiment, and opinion—and it has also been subject to polarized dialectic surrounding which particular paradigm was correct, or even "politically correct" (Grace, 1996). Many of these arguments have been based on opinions about methods and the validity of the assumed analogy between modern experiments and prehistoric knappers and tool users (Keeley, 1980; Odell and Odell-Vereecken, 1980; Gendel and Pirnay, 1982; Unrath et al., 1986; Lewenstein, 1987; Bamforth et al., 1990; Young and Bamforth, 1990). The problems of inferring use from marginal damage on stone tools, particularly utilized flakes, have produced a high level of consternation among lithic technologists and paramount frustration among contract archaeologists who are most pressed for time in determining site function and therefore site significance in management decisions—see Grace's (1996) review of the literature in *Archaeometry*.

One of the most commonly practiced techniques, and one of the most empirically frustrating, is inferring use-wear and therefore function from unmodified flakes. Studies that rely on readily available microscopic techniques are exceptions rather than the rule. Most archaeologists rely on macroscopic examination of flake margins, deriving inferences of prior use based on these gross morphological indications. Blind tests conducted with various researchers who examined experimentally produced specimens macroscopically have indicated that few archaeologists agree on the character of the damage and hence the implied function of the tool (Bamforth et al., 1990;

Young and Bamforth, 1990; Christensen and Walter, 1992; Christensen et al., 1992). The more "experienced" observers more often identified the use-wear correctly, but some did not. This finding serves as a warning since *the* most common flaked lithic tool found in prehistoric contexts is often the utilized flake. Young and Bamforth argue that "some degree of experimental experience should be required of all archaeologists who intend to include such tools in their research, simply to ensure that they observe their collections accurately" (1990, p. 408). Gaining some experience with archaeometric methods should carry equal importance (see Burroni et al., 2002). Young and Bamforth may be overoptimistic about the effectiveness of experience in diagnosing use-wear, and the error rate using macroscopic criteria is probably too high.

So what can archaeometry and analytical chemistry offer to solve the dilemma? Some studies by Marianne Christensen, Phillipe Walter, and others in France using environmental scanning electron microscopy (ESEM) may have far-reaching implications for use-wear research, and more recent studies using a variety of techniques have refined these efforts (Christensen et al., 1998; Evans and Donahue, 2005). Generally, even if one can determine the scraping, cutting, or rotary-wear utilization with some degree of confidence, it is rarely possible to determine the actual material upon which the tool was used beyond that it was a "hard or soft substance." Bone and wood are often lumped together as one material, but there are often important behavioral differences between stone tool use on one as opposed to the other.

Christensen et al. (1992; see also Christensen and Walter, 1992; and Menu and Walter, 1992) have explored margin polish (also referred to as "corn gloss" and "sickle sheen") on various stone tools by replicating experimental implements, using them, and employing ESEM with an EDXRF probe to yield qualitative elemental data that can be paired with the various substances against which the implements were used. The results were cross-checked using RBS (Rutherford backscattering spectrometry) and PIXE (proton-induced x-ray emission spectrometry). Another aspect of their research that cannot be treated in depth here is the empirical evidence for "melting silica," where the polish is essentially a combination of loss of lepispheric quartz (spherical aggregates of platy cristobalite or tridymite crystallites) from the chalcedony matrix of chert *and* an accumulation of material, in this case bone (see also Witthoft, 1967; Christensen et al., 1992, p. 491).

The importance of this work is that the material upon which a tool was used can be empirically defined. Quite similar and reliable data were also obtained with ESEM/EDXRF. The pilot study of Christensen et al. (1992) was applied to 13,000-year-old Magdalenian burins recovered from the important site of Étiolles in the Paris Basin that was thought to be a lithic production area. Their study indicated that some of the burins were used to modify "chalky matter," suggesting that the burins could have removed the chalk cortex of chert in the early stages of reduction (Christensen et al., 1992, pp. 492–493). Perhaps more illuminating was the analysis of Pre-dynastic Egyptian fish-tail knives and ripple-flaked knives that have often been considered uniquely for ritual purposes in contrast to household or other utilitarian functions. Using this technique, Christensen et al. concluded that the fish-tail knife was used to cut meat, and the ripple-flaked knife was used in plant cutting (1992; Menu: personal communication 1993). Most importantly, these several-thousand-year-old tools were museum pieces and handled by many people throughout their 100 + years of curation, and the technique is completely nondestructive when using the ESEM. While still experimental, the technique is readily available to most archaeologists worldwide and promises to solve some important issues that cannot be achieved with macroscopic and low-power microscopic techniques.

This study has been replicated and refined more recently using LA-ICP-MS by Evans and Donahue (2005). The authors not only used LA-ICP-MS to great effect, but they used even harsher cleaning techniques than the Christensen group a decade earlier and found that there was still not significant removal of the organic material (cf. Burroni et al., 2002). While ESEM and RBS are useful in determining the kind of material worked by tool users in prehistory, LA-ICP-MS is more efficient and, given that the instrumentation is becoming readily available at many universities, promises to revolutionize lithic use-wear studies in the twenty-first century.

Summary

Geoarchaeological petrology is steadily improving in its ability to assist the practice of lithic studies. Few archaeologists now think that a single analytical method is sufficient to characterize any stone material. Even obsidian, which is by definition completely disordered with no crystalline structure, has often been shown to exhibit source heterogeneity. While XRF is a good nondestructive tool for characterizing obsidian sources and artifacts, it may not always include enough elements to produce a distinctive characterization. Many regions in the world, including northern Mexico, Eurasia, and even parts of the USA and Canada, possess "unknown" sources that are still insufficiently studied to be useful in determining origins for stone objects recovered from the archaeological record. In contrast, many chert sources, particularly the Phanerozoic marine sediments that cover large regions (e.g., the Precambrian Ouachita Transition of the Edwards Plateau of Texas and the region of central France), reveal such substantial elemental and isotopic variability that it may be a long time until chert characterization studies approach the effectiveness of obsidian.

The most important general conclusion is that source assignment of any rock based on examination by eye alone is risky at best and simply does not work in many cases (Shackley, 2005, p. 101–105). Many of the techniques used to characterize rocks, most of them discussed here, are relatively inexpensive, and therefore, today's research should keep up with the latest improvements in direct measurement and analytical instrumentation.

Bibliograpahy

Ambrose, W. R., 1998. Obsidian hydration dating in a recent age obsidian mining site in Papua, New Guinea. In Shackley, M. S. (ed.), *Archaeological Obsidian Studies: Method and Theory.* New York: Plenum. Advances in Archaeological and Museum Science, Vol. 3, pp. 205–222.

Anovitz, L. M., Elam, J. M., Riciputi, L. R., and Cole, D. R., 1999. The failure of obsidian hydration dating: sources, implications, and new directions. *Journal of Archaeological Science*, **26**(7), 735–752.

Bamforth, D. B., Burns, G. R., and Woodman, C., 1990. Ambiguous use traces and blind test results: new data. *Journal of Archaeological Science*, **17**(4), 413–430.

Baxter, M. J., 1992. Archaeological uses of the biplot – a neglected technique? In Lock, G., and Moffet, J. (eds.), *Computer Applications and Quantitative Methods in Archaeology 1991*. Oxford: Tempus Reparatum. BAR International Series S577, pp. 141–148.

Baxter, M. J., 1994. Stepwise discriminant analysis in archaeometry: a critique. *Journal of Archaeological Science*, **21**(5), 659–666.

Bernard, H. R., 2006. *Research Methods in Anthropology: Qualitative and Quantitative Approaches*, 4th edn. Lanham, MD: Altamira Press.

Boyer, W. W., and Robinson, P., 1956. Obsidian artifacts of northwestern New Mexico and their correlation with source material. *El Palacio*, **63**(11–12), 333–345.

Burroni, D., Donahue, R. E., Pollard, A. M., and Mussi, M., 2002. The surface alteration features of flint artefacts as a record of environmental processes. *Journal of Archaeological Science*, **29**(11), 1277–1287.

Cann, J. R., and Renfrew, C., 1964. The characterization of obsidian and its application to the Mediterranean region. *Proceedings of the Prehistoric Society*, **30**, 111–133.

Carter, T., Poupeau, G., Bressy, C., and Pearce, N. J. G., 2006. A new programme of obsidian characterization at Çatalhöyük, Turkey. *Journal of Archaeological Science*, **33**(7), 893–909.

Cauvin, M.-C., and Balkan-Atlı, N., 1996. Rapport sur les recherches sur l'obsidienne en Cappdoce, 1993–1995. *Anatolica Antiqua*, **IV**, 249–271.

Christensen, M., and Walter, P., 1992. Physico-chimie en traceologie: Le cas des couteaux égyptiens. In Menu, M., and Walter, P. (eds.), *La pierre préhistorique: Actes du séminaire du laboratoire de recherche des musées de France, 13 et 14 dé cembre 1990*. Paris: Laboratoire de Recherche des Musées de France, pp. 149–171.

Christensen, M., Walter, P., and Menu, M., 1992. Usewear characterisation of prehistoric flints with IBA. *Nuclear Instruments and Methods in Physics Research, Section B: Beam Interactions with Materials and Atoms*, **64**(1–4), 488–493.

Christensen, M., Calligaro, T., Consigny, S., Dran, J.-C., Salomon, J., and Walter, P., 1998. Insight into the usewear mechanism of archaeological flints by implantation of a marker ion and PIXE analysis of experimental tools. *Nuclear Instruments and Methods in Physics Research, Section B: Beam Interactions with Materials and Atoms*, **136–138**, 869–874.

Church, T., 1995. Comment on "neutron activation analysis of stone from the Chadron formation and a Clovis site on the Great Plains" by Hoard et al. (1992). *Journal of Archaeological Science*, **22**(1), 1–5.

Craig, N., Speakman, R. J., Popelka-Filcoff, R. S., Glascock, M. D., Robertson, J. D., Shackley, M. S., and Aldenderfer, M. S., 2007. Comparison of XRF and PXRF for analysis of archaeological obsidian from southern Perú. *Journal of Archaeological Science*, **34**(12), 2012–2024.

Davis, M. K., Jackson, T. L., Shackley, M. S., Teague, T., and Hampel, J. H., 2011. Factors affecting the energy-dispersive x-ray fluorescence (EDXRF) analysis of archaeological obsidian. In Shackley, M. S. (ed.), *X-Ray Fluorescence Spectrometry (XRF) in Geoarchaeology.* New York: Springer, pp. 45–64.

Deal, K., 2002. Effects of prescribed fire on obsidian and implications for reconstructing past landscape conditions. In Loyd, J. M., Origer, T. M., and Fredrickson, D. A. (eds.), *The Effects of Fire and Heat on Obsidian*. California: U.S. Department of the Interior, Bureau of Land Management, pp. 15–43. Cultural Resources Publication.

Delage, C., 2003. *Siliceous Rocks and Prehistory: Bibliography on Geo-archaeological Approaches to Chert Sourcing and Prehistoric Exploitation*. Oxford: Hadrian Books. BAR International Series, Vol. 1168.

Ericson, J. E., and Kimberlin, J., 1977. Obsidian sources, chemical characterization and hydration rates in west Mexico. *Archaeometry*, **19**(2), 157–166.

Evans, A. A., and Donahue, R. E., 2005. The elemental chemistry of lithic microwear: an experiment. *Journal of Archaeological Science*, **32**(12), 1733–1740.

Friedman, I., and Smith, R. L., 1960. A new dating method using obsidian. Part I, the development of the method. *American Antiquity*, **25**(4), 476–493.

Friedman, I., Trembour, F. W., and Hughes, R. E., 1997. Obsidian hydration dating. In Taylor, R. E., and Aitken, M. J. (eds.), *Chronometric Dating in Archaeology.* New York: Plenum Press. Advances in Archaeological and Museum Science, Vol. 2, pp. 297–321.

Gendel, P. A., and Pirnay, L., 1982. Microwear analysis of experimental flint tools: further experimental results. *Studia Praehistorica Belgica*, **2**, 251–265.

Glascock, M. D., 1991. *Tables for Neutron Activation Analysis*, 3rd edn. Columbia: Research Reactor Facility, University of Missouri.

Glascock, M. D., 1994. New world obsidian: recent investigations. In Scott, D. A., and Meyers, P. (eds.), *Archaeometry of Pre-Columbian Sites and Artifacts: Proceedings of a Symposium Organized by the UCLA Institute of Archaeology and the Getty Conservation Institute, Los Angeles, California, March 23–27, 1992*. Los Angeles: Getty Conservation Institute, pp. 113–134.

Glascock, M. S., 2011. Comparison and contrast between XRF and NAA: used for characterization of obsidian sources in central Mexico. In Shackley, M. S. (ed.), *X-Ray Fluorescence Spectrometry (XRF) in Geoarchaeology.* New York: Springer, pp. 161–192.

Glascock, M. D., Braswell, G. E., and Cobean, R. H., 1998. A systematic approach to obsidian source characterization. In Shackley, M. S. (ed.), *Archaeological Obsidian Studies: Method and Theory.* New York: Plenum. Advances in Archaeological and Museum Science, Vol. 3, pp. 15–65.

Glascock, M. D., Speakman, R. J., and Pollard, H. P., 2005. LA-ICP-MS as a supplement to abbreviated-INAA for obsidian artifacts from the Aztec-Tarascan frontier. In Speakman, R. J., and Neff, H. (eds.), *Laser Ablation ICP-MS in Archaeological Research*. Albuquerque: University of New Mexico Press, pp. 29–36.

Glascock, M. D., Speakman, R. J., and Neff, H., 2007. Archaeometry at the University of Missouri Research Reactor and the provenance of obsidian artefacts of North America. *Archaeometry*, **49**(2), 343–357.

Goffer, Z., 1980. *Archaeological Chemistry: A Sourcebook on the Applications of Chemistry to Archaeology.* New York: Wiley. Chemical Analysis, Vol. 55.

Grace, R., 1996. Use-wear analysis: the state of the art. *Archaeometry*, **38**(2), 209–229.

Gratuze, B., 1999. Obsidian characterization by laser ablation ICP-MS and its application to prehistoric trade in the Mediterranean and the Near East: sources and distribution of obsidian with the Aegean and Anatolia. *Journal of Archaeological Science*, **26**(8), 869–881.

Green, R. C., 1962. Obsidian, its application to archaeology. *New Zealand Archaeological Society Newsletter*, **5**, 8–16.

Green, R. C., 1998. A 1990s perspective on method and theory in archaeological volcanic glass studies. In Shackley, M. S. (ed.), *Archaeological Obsidian Studies: Method and Theory*. New York: Plenum. Advances in Archaeological and Museum Science, Vol. 3, pp. 223–235.

Hall, M. C., and Jackson, R. J., 1989. Obsidian hydrations rates in California. In Hughes, R. E. (ed.), *Current Directions in California Obsidian Studies*. Berkeley: University of California. University of California Archaeological Research Facility Contributions, Vol. 48, pp. 31–59.

Harbottle, G., 1982. Chemical characterization in archaeology. In Ericson, J. E., and Earle, T. K. (eds.), *Contexts for Prehistoric Exchange*. New York: Academic, pp. 13–51.

Hildreth, W., 1981. Gradients in silicic magma chambers: implications for lithospheric magmatism. *Journal of Geophysical Research – Solid Earth*, **86**(B11), 10153–10192.

Hoard, R. J., Holen, S. R., Glascock, M. D., and Neff, H., 1995. Additional comments on neutron activation analysis of stone from the Great Plains: reply to Church. *Journal of Archaeological Science*, **22**(1), 7–10.

Högberg, A., and Olausson, D. S., 2007. *Scandinavian Flint: An Archaeological Perspective*. Aarhus, Denmark: Aarhus University Press.

Hughes, R. E., 1984a. Obsidian studies in the Great Basin: problems and prospects. In Hughes, R. E. (ed.), *Obsidian Studies in the Great Basin*. Berkeley: University of California. Contributions of the University of California Archaeological Research Facility, Vol. 45, pp. 1–19.

Hughes, R. E., 1984b. *Obsidian Studies in the Great Basin*. Berkeley: Archaeological Research Facility, Department of Anthropology, University of California. Contributions of the University of California Archaeological Research Facility, Vol. 45.

Hughes, R. E., 1988. The Coso volcanic field reexamined: implications for obsidian sourcing and hydration dating research. *Geoarchaeology*, **3**(4), 253–265.

Hughes, R. E., 1994. Intrasource separation of artefact-quality obsidians from the Casa Diablo area, California. *Journal of Archaeological Science*, **21**(2), 263–271.

Hughes, R. E., and Smith, R. L., 1993. Archaeology, geology, and geochemistry in obsidian provenance studies. In Stein, J. K., and Linse, A. R. (eds.), *Effects of Scale on Archaeological and Geoscientific Perspectives*. Boulder: Geological Society of America. Geological Society of America Special Paper, Vol. 283, pp. 79–91.

Hughes, R. E., Högberg, A., and Olausson, D., 2012. The chemical composition of some archaeologically significant flint from Denmark and Sweden. *Archaeometry*, **54**(5), 779–795.

Hull, K. L., 2001. Reasserting the utility of obsidian hydration dating: a temperature-dependent empirical approach to practical temporal resolution with archaeological obsidians. *Journal of Archaeological Science*, **28**(10), 1025–1240.

Hull, K. L., 2002. *Culture Contact in Context: A Multiscalar View of Catastrophic Depopulation and Culture Change in Yosemite Valley, California*. PhD dissertation, University of California, Berkeley.

Jack, R. N., and Carmichael, I. S. E., 1969. The chemical "fingerprinting" of acid volcanic rocks. *California Division of Mines and Geology, Special Report*, **100**, 17–32.

Jack, R. N., and Heizer, R. F., 1968. "Finger-printing" of some Mesoamerican obsidian artifacts. *Contributions of the University of California Archaeological Research Facility*, **5**, 81–100.

Jackson, R. J., 1984. Current problems in obsidian hydration analysis. In Hughes, R. E. (ed.), *Obsidian Studies in the Great Basin*. Berkeley: Archaeological Research Facility, Department of Anthropology, University of California. Contributions of the University of California Archaeological Research Facility, Vol. 45, pp. 103–116.

Jackson, T. L., 1986. *Late Prehistoric Obsidian Exchange in Central California*. Unpublished PhD dissertation, Department of Anthropology, Stanford University.

Jackson, T. L., 1989. Late prehistoric obsidian production and exchange in the North Coast Ranges, California. In Hughes, R. E. (ed.), *Current Directions in California Obsidian Studies*. Berkeley: Archaeological Research Facility, Department of Anthropology, University of California. Contributions of the University of California Archaeological Research Facility, Vol. 48, pp. 79–94.

Judge, W. J., and Sebastian, L., 1988. *Quantifying the Present and Predicting the Past: Theory, Method, and Application of Archaeological Predictive Modeling*. Denver: U.S. Department of the Interior, Bureau of Land Management.

Keeley, L. H., 1980. *Experimental Determinations of Stone Tool Uses: A Microwear Analysis*. Chicago: University of Chicago Press.

Kempe, D. R. C., and Harvey, A. P. (eds.), 1983. *The Petrology of Archaeological Artefacts*. Oxford: Clarendon Press.

Kuzmin, Y. V., Popov, V. K., Glascock, M. D., and Shackley, M. S., 2002. Sources of archaeological volcanic glass in the Primorye (Maritime) Province, Russian Far East. *Archaeometry*, **44**(4), 505–515.

Layton, T. N., 1973. Temporal ordering of surface-collected artifacts by hydration measurement. *Archaeometry*, **15**(1), 129–132.

Lewenstein, S. M., 1987. *Stone Tool Use at Cerros: The Ethnoarchaeological and Use-Wear Evidence*. Austin: University of Texas Press.

Liritzis, I., 2006. SIMS-SS, a new obsidian hydration dating method: analysis and theoretical principles. *Archaeometry*, **48**(3), 533–547.

Loyd, J. M., 2002. Rehydration of burned obsidian. In Loyd, J. M., Origer, T. M., and Fredrickson, D. A. (eds.), *The Effects of Fire and Heat on Obsidian*. Denver: U.S. Department of the Interior, Bureau of Land Management. Cultural Resources Publication, pp. 135–140.

Loyd, J. M., Origer, T. M., and Fredrickson, D. A., 2002. *The Effects of Fire and Heat on Obsidian*. Denver: U.S. Department of the Interior, Bureau of Land Management. Cultural Resources Publication.

Luedtke, B. E., 1992. *An Archaeologist's Guide to Chert and Flint*. Los Angeles: University of California. Archaeological Research Tools, Vol. 7.

Luedtke, B. E., and Meyers, J. T., 1984. Trace element variation in Burlington chert: a case study. In Butler, B. M., and May, E. E. (eds.), *Prehistoric Chert Exploitation: Studies from the*

Midcontinent. Carbondale: Southern Illinois University. Center for Archaeological Investigations Occasional Paper, Vol. 2, pp. 287–298.

MacDonald, R., Davies, G. R., Bliss, C. M., Leat, P. T., Bailey, D. K., and Smith, R. L., 1987. Geochemistry of high-silica peralkaline rhyolites, Naivasha, Kenya Rift Valley. *Journal of Petrology*, **28**(6), 979–1008.

Mahood, G. A., and Hildreth, W., 1983. Large partition coefficients for trace elements in high-silica rhyolites. *Geochimica et Cosmochimica Acta*, **47**(1), 11–30.

Matiskainen, H., Vuorinen, A., and Burman, O., 1989. The provenance of prehistoric flint in Finland. In Maniatis, Y. (ed.), *Archaeometry, Proceedings of the 25th International Symposium*. Amsterdam: Elsevier, pp. 625–643.

Menu, M., and Walter, P., 1992. Alliage de disciplines: matières et techniques lithiques en préhistoire. In Menu, M., and Walter, P. (eds.), *La pierre préhistorique: Actes du séminaire du laboratoire de recherche des musées de France, 13 et 14 dé cembre 1990*. Paris: Laboratoire de Recherche des Musées de France, pp. 195–200.

Michels, J. W., Tsong, I. S. T., and Smith, G. A., 1983. Experimentally derived hydration rates in obsidian dating. *Archaeometry*, **25**(2), 107–117.

Neff, H., and Glascock, M. D., 1995. The state of nuclear archaeology in North America. *Journal of Radioanalytical and Nuclear Chemistry*, **196**(2), 275–286.

Nelson, F. W., Jr., 1984. X-ray fluorescence analysis of some western North American obsidians. In Hughes, R. E. (ed.), *Obsidian Studies in the Great Basin*. Berkeley: Archaeological Research Facility, Department of Anthropology, University of California. Contributions of the University of California Archaeological Research Facility, Vol. 45, pp. 27–62.

Odell, G. H., 2003. *Lithic Analysis*. New York: Springer Science.

Odell, G. H., and Odell-Vereecken, F., 1980. Verifying the reliability of lithic use-wear assessments by 'blind tests': the low power approach. *Journal of Field Archaeology*, **7**(1), 87–120.

Ratté, J. C., 2004. A guide to the Mule Creek volcanic vent, the rhyolite of Potholes Country, and obsidian ledges, Gila National Forest, southwestern New Mexico. *New Mexico Geology*, **26**(4), 111–122.

Ridings, R., 1996. Where in the world does obsidian hydration dating work? *American Antiquity*, **61**(1), 136–148.

Roll, T. E., Neeley, M. P., Speakman, R. J., and Glascock, M. D., 2005. Characterization of Montana cherts by LA-ICP-MS. In Speakman, R. J., and Neff, H. (eds.), *Laser Ablation ICP-MS in Archaeological Research*. Albuquerque: University of New Mexico Press, pp. 58–74.

Shackley, M. S., 1988. Sources of archaeological obsidian in the southwest: an archaeological, petrological, and geochemical study. *American Antiquity*, **53**(4), 752–772.

Shackley, M. S., 1995. Sources of archaeological obsidian in the greater American Southwest: an update and quantitative analysis. *American Antiquity*, **60**(3), 531–551.

Shackley, M. S., 1998a. Gamma rays, x-rays and stone tools: some current advances in archaeological geochemistry. *Journal of Archaeological Science*, **25**(3), 259–270.

Shackley, M. S. (ed.), 1998b. *Archaeological Obsidian Studies: Method and Theory*. New York: Plenum Press. Advances in Archaeological and Museum Science, Vol. 3.

Shackley, M. S., 1998c. Intrasource chemical variability and secondary depositional processes: lessons from the American Southwest. In Shackley, M. S. (ed.), *Archaeological Obsidian Studies: Method and Theory*. New York: Plenum. Advances in Archaeological and Museum Science, Vol. 3, pp. 83–102.

Shackley, M. S., 2002. Precision versus accuracy in the XRF analysis of archaeological obsidian: some lessons for archaeometry and archaeology. In Jerem, E., and Biró, K. T. (eds.), *Archaeometry 98: Proceedings of the 31st International Symposium on Archaeometry, Budapest, Hungary, April 26–May 3, 1998*. Oxford: Archaeopress. Archaeolingua, Central European Series 1. British Archaeological Reports, International Series 1043., Vol. 2, pp. 805–810.

Shackley, M. S., 2005. *Obsidian: Geology and Archaeology in the North American Southwest*. Tucson: University of Arizona Press.

Shackley, M. S., 2008. Archaeological petrology and the archaeometry of lithic materials. *Archaeometry*, **50**(2), 194–215.

Shackley, M. S., 2011. An introduction to X-Ray fluorescence (XRF) analysis in archaeology. In Shackley, M. S. (ed.), *X-Ray Fluorescence Spectrometry (XRF) in Geoarchaeology*. New York: Springer, pp. 7–44.

Shackley, M. S., 2013. The Secondary distribution of archaeological obsidian in Rio Grande quaternary Sediments, Jemez Mountains to San Antonito, New Mexico: inferences for Paleoamerican procurement and the Age of Sediments. Poster presented at the Paleoamerican Odyssey Conference, Santa Fe, October, 2013.

Shackley, M. S., and Dillian, C., 2002. Thermal and environmental effects on obsidian geochemistry: experimental and archaeological evidence. In Loyd, J. M., Origer, T. M., and Fredrickson, D. A. (eds.), *The Effects of Fire and Heat on Obsidian*. Denver: U.S. Department of the Interior, Bureau of Land Management. Cultural Resources Publication, pp. 117–134.

Skinner, C. E., 1983. *Obsidian Studies in Oregon: An Introduction to Obsidian and Investigations of Selected Methods of Obsidian Characterization Utilizing Obsidian Collected at Prehistoric Quarry Sites in Oregon*. Master's project, Interdisciplinary Studies, University of Oregon.

Skinner, C. N., 2002. Fire regimes and fire history: implications for obsidian hydration dating. In Loyd, J. M., Origer, T. M., and Fredrickson, D. A. (eds.), *The Effects of Fire and Heat on Obsidian*. Denver: U.S. Department of the Interior, Bureau of Land Management. Cultural Resources Publication, pp. 147–152.

Skinner, C. E., Thatcher, J. J., and Davis, M. K., 1997. *X-ray Fluorescence and Obsidian Hydration Rim Measurement of Artifact Obsidian from 35-DS-193 and 35-DS-201, Surveyor Fire Rehabilitation Project, Deschutes National Forest, Oregon*. Corvallis, OR: Northwest Research Obsidian Studies Laboratory Report 98-96.

Speakman, R. J., and Glascock, M. D. (eds.), 2007. Special issue: acknowledging fifty years of neutron activation analysis in archaeology. *Archaeometry*, **49**(2), 179–420.

Speakman, R. J., and Neff, H. (eds.), 2005. *Laser Ablation ICP-MS in Archaeological Research*. Albuquerque: University of New Mexico Press.

Speakman, R. J., and Shackley, M. S., 2012. Silo science and portable XRF in archaeology: a response to Frahm. *Journal of Archaeological Science*, **40**(2), 1435–1443.

Steffen, A., 2002. The Dome Fire pilot project: extreme obsidian fire effects in the Jemez Mountains. In Loyd, J. M., Origer, T. M., and Fredrickson, D. A. (eds.), *The Effects of Fire and Heat on Obsidian*. Denver: U.S. Department of the Interior, Bureau of Land. Cultural Resources Publication, pp. 159–202.

Stevenson, C. M., Freeborn, W. P., and Scheetz, B. E., 1987. Obsidian hydration dating: an improved optical technique for measuring the width of the hydration rim. *Archaeometry*, **29**(1), 120–123.
Stevenson, C. M., Carpenter, J., and Scheetz, B. E., 1989. Obsidian dating: recent advances in the experimental determination and application of hydration rates. *Archaeometry*, **31**(2), 193–206.
Stevenson, C. M., Mazer, J. J., and Sheetz, B. E., 1998. Laboratory obsidian hydration rates: theory, method, and application. In Shackley, M. S. (ed.), *Archaeological Obsidian Studies: Method and Theory*. New York: Plenum. Advances in Archaeological and Museum Science, Vol. 3, pp. 181–204.
Summerhayes, G. R., Bird, J. R., Fullagar, R., Gosden, C., Specht, J., and Torrence, R., 1998. Applications of PIXE-PIGME to archaeological analysis of changing patterns of obsidian use in West New Britain, Papua New Guinea. In Shackley, M. S. (ed.), *Archaeological Obsidian Studies: Method and Theory*. New York: Plenum. Advances in Archaeological and Museum Science, Vol. 3, pp. 129–158.
Thomas, D. H., 1986. *Refiguring Anthropology*. Prospect Heights, IL: Waveland Press.
Torrence, R., 1992. What is Lapita about obsidian? A view from the Talasea sources. In Galipaud, J.-C. (ed.), *Poterie Lapita et peuplement: actes du Colloque Lapita, Nouméa, Nouvelle Calé donie*. Nouméa, NC: O.R.S.T.O.M., pp. 111–126.
Tykot, R. H., 1992. The sources and distribution of Sardinian obsidian. In Tykot, R. H., and Andrews, T. K. (eds.), *Sardinia in the Mediterranean: A Footprint in the Sea*. Sheffield: Sheffield Academic Press, pp. 57–70.
Tykot, R. H., 1998. Mediterranean islands and multiple flows: the sources and exploitation of Sardinian obsidian. In Shackley, M. S. (ed.), *Archaeological Obsidian Studies: Method and Theory*. New York: Plenum. Advances in Archaeological and Museum Science, Vol. 3, pp. 67–82.
Tykot, R. H., and Young, S. M. M., 1995. Archaeological applications of inductively coupled plasma-mass spectrometry. In Orna, M. V. (ed.), *Archaeological Chemistry: Organic, Inorganic, and Biochemical Analysis*. Washington, DC: American Chemical Society. ACS Symposium Series, Vol. 625, pp. 116–130.
Unrath, G., Owen, L. R., van Gijn, A. L., Moss, E. H., Plisson, H., and Vaughn, P., 1986. An evaluation of microwear studies: a - multi-analyst approach. *Early Man News*, **9–11**, 117–176.
Warashina, T., 1992. Allocation of jasper archaeological implements by means of ESR and XRF. *Journal of Archaeological Science*, **19**(4), 357–373.
Ward, G., 1977. On the ease of 'sourcing' artefacts and the difficulty of 'knowing' prehistory. *New Zealand Archaeological Association Newsletter*, **20**(3), 188–194.
What is XRF? n.d. http://www.swxrflab.net/xrfinstrument.htm.
Williams-Thorpe, O., 1995. Obsidian in the Mediterranean and the Near East: a provenancing success story. *Archaeometry*, **37**(2), 217–248.
Witthoft, J., 1967. Glazed polish on flint tools. *American Antiquity*, **32**(3), 383–388.
Young, D., and Bamforth, D. B., 1990. On the macroscopic identification of used flakes. *American Antiquity*, **55**(2), 403–409.

Cross-references

Field Geochemistry
Geochemical Sourcing
Inductively Coupled Plasma-Mass Spectrometry (ICP-MS)
Petrography
Scanning Electron Microscopy (SEM)
Volcanoes and People
X-ray Fluorescence (XRF) Spectrometry in Geoarchaeology

LIVING SURFACES

Erin C. Dempsey[1] and Rolfe D. Mandel[2]
[1]National Park Service, Midwest Archeological Center, Lincoln, NE, USA
[2]Department of Anthropology, University of Kansas, Lawrence, KS, USA

Introduction

When people spend a period of time in one spot on the earth's surface, a signature of that occupation is often recorded in the place at which they stopped. Such surfaces are referred to as *living surfaces*, and evidence they contain indicates a human presence. Information on human behavior, such as subsistence strategies, tool making, and other activities, as well as length of occupation and population size, may be gleaned from living surfaces preserved in the archaeological record. Generally, such living surfaces occur as discrete units that reflect a particular occupation or activity at a particular point in time (Dibble et al., 1997). Living surfaces are often defined by their chemical and physical characteristics, though the spatial distribution of artifacts and features is also critical for understanding human behavior at an archaeological site.

Living surfaces are formed in various ways. When humans discard artifacts on the surface, introduce organic matter into soil or sediment, or disturb a surface by other actions, they leave signatures that can be detected using a number of techniques. Living surfaces may be visible to the naked eye, appearing as dark stains in the soil or sediment, or they may be marked by the presence of artifacts, charcoal, and/or burned earth. In other cases, living surfaces may be identified only through geochemical analyses. The combination of all three methods may be the most effective way to identify the presence or absence of a living surface.

Geoarchaeology has become an important component in the investigation of living surfaces. Specifically, geoarchaeologists often play critical roles in identifying and tracing living surfaces (i.e., archaeological prospection) and assessing the vertical and horizontal integrity of cultural deposits associated with such surfaces. Also, by using geochemical prospection and micromorphological analysis, they contribute to the identification of specific activity areas on living surfaces.

Formation of living surfaces

All archaeological sites consist of at least one living surface, though such a surface may in reality represent a palimpsest of multiple unrelated occupations succeeding each other over time. The characteristics of living surfaces vary depending on the length of occupation and the types of activities performed at the site. A thick, dark, organic-rich soil may be indicative of a long-term occupation where cooking and other activities resulted in the deposition of charcoal, ash, and other organic waste. To produce such a deposit, people might have disposed of food remains, charcoal, and other organic matter into the soil over an extended period of time, creating a distinct horizon that is visible in the stratigraphy. These horizons would also have a strong and distinctive geochemical signature compared to the natural stratigraphy. *Terra preta*, a type of Amazonian Dark Earth of South America, provides a good example of this kind of living surface (see the entry on Anthrosols in this volume). Though there are several hypotheses concerning how they were formed, it is generally accepted that *terra preta* represents an anthropogenic or anthropic soil, created as people continuously occupied an area for decades, adding organic matter to the soil from cooking, eating, and living (Eden et al., 1984; Woods and McCann, 1999; McCann et al., 2001; Neves et al., 2003; Glaser and Woods, 2004). In Europe, degradation of construction materials and occupation deposits associated with Roman and Classical period urban sites also forms dark earths that mark former living surfaces (Macphail and Courty, 1985; Yule, 1990; Goldberg and Macphail, 2006, pp. 271–272, 274–275, Tables 13.1 and 13.2). Thick, dark layers that often appear to be homogenous are characteristic of European Dark Earths (Borderie et al., 2015); however, micromorphological and geochemical analyses have revealed that the layers are typically anything but homogeneous and often display internal bedding (Macphail, 2002).

On the opposite end of the spectrum from a long-term occupation and associated, well-established living surface, the presence of a few artifacts in an otherwise unremarkable soil horizon may represent short-term site use. A scatter of stone artifacts that is not associated with a hearth or structure may be evidence of a site where a person or small group passed through the area but did not stay long. At these sites, a few artifacts may be the only visible evidence that a human or humans occupied the space. For example, in the open grasslands of south-central and southwestern South Dakota, bison migrated between the open prairie and the forested Black Hills. As such, many archaeological sites in the badland and grassland areas are small lithic scatters, possibly left behind as people followed the large game. The badland area also contains excellent raw material quarries. Sites near the quarries tend to consist of tested cobbles, flakes, and hammerstones (Hannus et al., 2003; Dempsey, 2014). At these sites, people picked up the raw material, determined if it was workable, took what they needed, and then moved on. These living surfaces do not have the thickness or organic content of the *terra preta* or European Dark Earths, but they constitute an important kind of living surface that helps archaeologists interpret the record of past human behavior.

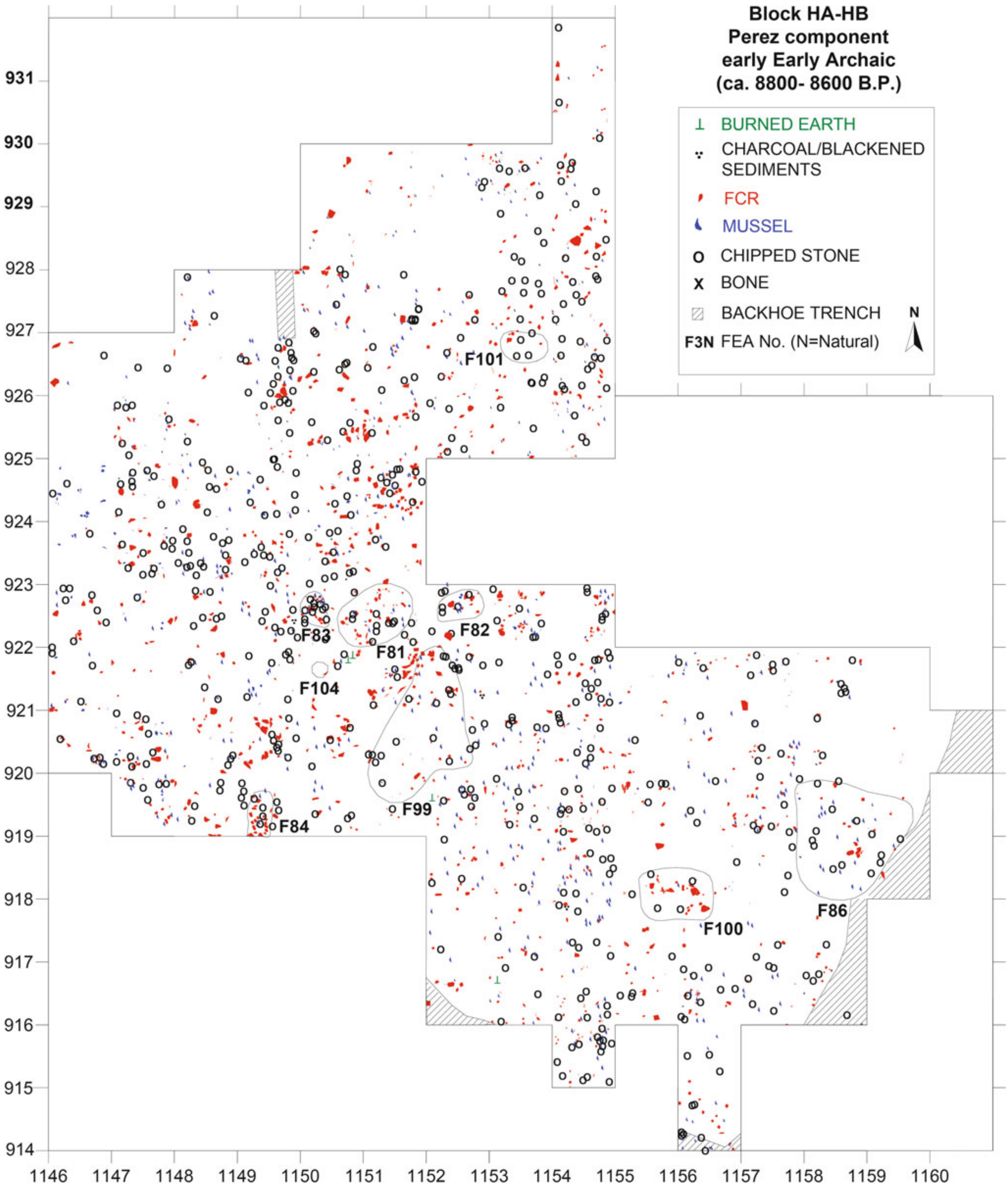
Many recorded prehistoric open-air archaeological sites fall somewhere between a long- and short-term occupation, and the associated living surfaces often have fairly dense concentrations of artifacts, but there is little or no evidence of soil *melanization* (i.e., darkening from the accumulation of organic matter). For example, at the Richard Beene site in south-central Texas, at least 20 discrete living surfaces spanning the past ca. 10,000 years were recorded in the upper 12 m of alluvial fill beneath a terrace of the Medina River (Thoms and Mandel, 2007). Nearly all of the living surfaces were represented by dense concentrations of artifacts (mostly chipped stone and fire-cracked rock) that were products of decades of occupation by hunter-gatherers on a former floodplain. Despite the abundance of cultural deposits (Figs. 1 and 2), none of the buried soils with living surfaces at Richard Beene are melanized (Mandel et al., 2007).

In caves and rock-shelters, combustion features are often associated with living surfaces, and in some cases, most of the cultural deposits in these protected settings consist of charcoal and ash (Goldberg and Mandel, 2008). For example, one of the striking characteristics of the deposits at Kebara Cave in Israel is the abundance of ashy combustion features associated with Middle Paleolithic living surfaces (Figure 3) (Meignen et al., 1989, 2001; Goldberg and Macphail, 2006, pp. 180–185). Large, prominent combustion features indicative of Paleolithic living surfaces have been recorded in other caves in the Middle East, including Tabun and Hayonim (Goldberg and Bar-Yosef, 1998), as well as in Middle Stone Age caves in South Africa, such as Klasies River Mouth, Die Kelders, and Blombos (Singer and Wymer, 1982; Marean et al., 2000).

It is important to note that living surfaces are preserved in a variety of environmental and geomorphic contexts. Caves, rock-shelters, pond or lake margins, springs, and wetlands often contain excellent examples of living surfaces for two reasons: (1) they are settings that attract humans and their prey, and/or (2) they are areas of good archaeological preservation (Ashley, 2001; Farrand, 2001; Feibel, 2001; Mandel et al., 2014). At sites in these contexts, living surfaces and other strata are often rapidly buried by sediment, and therefore lengthy exposure of such surfaces to the elements is limited. Open-air sites that occur on hilltops or along streambanks, though often equally as attractive as the localities listed above, may be less amenable to preservation because of dynamism in the taphonomic processes occurring at an elevated or fluvial site that experiences frequent or continual episodes of erosion. Living surfaces may be differentially preserved in these locations depending on the history of climate change, the density of vegetative cover, the erodibility of the sediment or bedrock, and other factors.

Identifying living surfaces

Living surfaces may be identified through several methods including visual identification of physical characteristics, geochemical analyses of soils and sediments, and geophysical techniques. A visual reconnaissance is likely the first technique the archaeologist uses to identify a living surface, the physical characteristics of which vary depending on how the surface formed. Visible differences



Living Surfaces, Figure 1 Plan view showing the distribution of deeply buried cultural materials on the Early Archaic (ca. 8800–8600 BP) living surface in Block HA-HB at the Richard Beene site, south-central Texas (From Clabaugh and Thoms, 2007, Figure 13.28).

Living Surfaces, Figure 2 A concentration of fire-cracked rock and chipped stone artifacts (red tape) marks the deeply buried Angostura (Late Paleo-Indian/Early Archaic) living surface at the Richard Beene site (Photograph by Rolfe Mandel).

in soil color, hardness or compaction of sediment or soil, and the presence of artifacts may be primary indicators that a living surface has been preserved. The distribution of artifacts and features across a living surface is an important component of interpreting behavior and formation processes at the site. Activity areas may be identified based on the distribution of cultural material. Though activity-specific remains may not occur as discrete units, analysis of microartifacts, microstratigraphy, and careful site mapping may reveal significant patterns of site use. Often, though, living surfaces are not recognizable through a visual inspection. In those cases, chemical prospecting is useful.

With geochemical prospecting, the basic premise is that certain chemical compounds are deposited in soils and sediments as a result of particular human activities (Wells and Terry, 2007; Luzzadder-Beach et al., 2011). For example, phosphorus, an element (and its compounds) that has been analyzed in archaeological research and geochemical prospection for a long time (Linderholm, 2007), is often associated with the preparation and consumption of foods and beverages. Also, sodium and potassium compounds are by-products of wood ash in hearths and kilns, and iron oxide and mercuric sulfide accumulate in soils as a result of certain pigments, such as hematite and cinnabar, commonly used in ceremonial settings such as burials and caches (Wells and Terry, 2007). These chemical compounds, especially those of phosphorus, are rapidly fixed to the mineral surfaces of sediments and tend to remain stable and immobile for long periods in most soil systems (Tiessen, 1995); hence, they are good proxies for various human activities on living surfaces.

Geochemical prospection has been used to locate and delimit site boundaries (e.g., Aston et al., 1998; Schlezinger and Howes, 2000; Haslam and Tibbett, 2004), and it also frequently serves to detect and analyze ancient living surfaces and associated activity areas (Sánchez Vizcaíno and Cañabate, 1999; Fernández et al., 2002; Hutson et al., 2009). The application of geochemical prospection has been especially critical to the evolution of Mesoamerican archaeological research (Dunning et al., 2015). For example, at Piedras Negras, Guatemala, Parnell et al. (2002) found phosphorus to be the most useful indicator of human activities, especially those involving food processing and disposal. At the rapidly abandoned site of Aguateca, Guatemala, Terry et al. (2004) demonstrated a strong relationship between phosphorus and artifact assemblages indicative of food processing and consumption. Cook et al. (2006) used inductively coupled plasma mass spectrometry (ICP-MS) analysis to test for 60 major, minor, and rare earth elements collected from living surfaces at the ancient site of Cancuen, Guatemala, with 30 elements showing enrichment compared to control areas. The most notable concentrations were of mercury and gold, which are by-products of the processing of cinnabar as a pigment and jade for ornamentation, respectively. Testing of a portable X-ray fluorescence scanner (pXRF) at the Colonial era Hacienda Telchaquillo in Yucatan indicates that this unit is useful in detecting trace metals on living surfaces, but not for detecting the presence of phosphorus (Coronel et al., 2014).

Geophysical techniques also may help identify living surfaces, particularly those that are buried. For decades, subsurface remote sensing techniques, such as magnetometry, ground-penetrating radar, resistivity, and electrical conductivity, have been used to identify buried living surfaces (e.g., Kvamme, 2001; Banning, 2002; Gaffney and Gater, 2003; Conyers, 2004, p. 146; Venter et al., 2006; Arciniega-Ceballos et al., 2009). These methods are adept at identifying near-surface cultural deposits and developing focused research programs for their study. Geophysical methods are particularly useful for understanding the distribution of living surfaces across a site, as well as differences in construction methods and variability in cultural and natural site processes (Thompson et al., 2011).

Merging different field methods and laboratory analyses has proven effective in detecting and tracing buried

Living Surfaces, Figure 3 (**a**) A sequence of combustion features and anthropogenic deposits associated with Middle Paleolithic living surfaces at Kebara Cave, Israel. The whitish zones were originally calcareous ash accumulations, which have been subsequently altered by diagenesis to apatite (calcium phosphate) or other phosphate minerals. The photo scale is 50 cm long. (**b**) Macrophotograph of the sequence of thin combustion zones from the Middle Paleolithic living surfaces at Kebara Cave shown in (**a**). Note the dark charcoal-rich layers overlain by lighter ash. The length of the macrophotograph is 75 mm (From Goldberg and Mandel, 2008, Figure 6).

living surfaces at archaeological sites. For example, Dirix et al. (2013) combined geochemical prospection and coring with geophysical techniques to detect buried living surfaces at a site in Sagalassos, Turkey. At the McNeal Alluvial Fan (site 13MC15) in Eastern Iowa, Mandel et al. (2006) combined deep coring and soil micromorphological analysis to locate and trace buried archaic living surfaces marked by concentrations of charcoal and micro-debitage. Similarly, Hajic et al. (2007) used cores and soil micromorphology to determine the spatial limits of deeply buried Paleo-Indian living surfaces at the Big Eddy Site in southwestern Missouri.

Bibliography

Arciniega-Ceballos, A., Hernandez-Quintero, E., Cabral-Cano, C. E., Morett-Alatorre, L., Diaz-Molina, O., Soler-Arechalde, A., and Chavez-Segura, R., 2009. Shallow geophysical survey at the archaeological site of San Miguel Tocuila, Basin of Mexico. *Journal of Archaeological Science*, **36**(6), 1199–1205.

Ashley, G. M., 2001. Archaeological sediments in springs and wetlands. In Stein, J. K., and Farrand, W. R. (eds.), *Sediments in Archaeological Context*. Salt Lake City: The University of Utah Press, pp. 183–210.

Aston, M. A., Martin, M. H., and Jackson, A. W., 1998. The potential for heavy metal soil analysis on low status archaeological sites at Shapwick, Somerset. *Antiquity*, **72**(278), 838–847.

Banning, E. B., 2002. *Archaeological Survey*. New York: Kluwer Academic/Plenum Press.

Borderie, Q., Devos, Y., Nicosia, C., Cammas, C., and Macphail, R., 2015. Dark Earth in the geoarchaeological approach to urban contexts. In Carcaud, N., and Arnaud-Fassetta, G. (eds.), *La Gé oarchéologie Française au XXIe Siècle/French Geoarchaeology in the 21st Century*. Paris: Editions CNRS, pp. 213–223.

Clabaugh, P. A., and Thoms, A. T., 2007. Feature variability at the Richard Beene site. In Thoms, A. V., and Mandel, R. D. (eds.), *Archaeological and Paleoecological Investigations at the Richard Beene Site (41BX831), South Central Texas*. College Station, TX: Texas A&M University. Center for Ecological Archaeology, Reports of Investigations no, Vol. 8, pp. 251–304.

Conyers, L. B., 2004. *Ground-Penetrating Radar for Archaeology*. Walnut Creek, CA: AltaMira Press.

Cook, D. E., Kovacevich, B., Beach, T., and Bishop, R., 2006. Deciphering the inorganic chemical record of ancient human activity using ICP-MS: a reconnaissance study of late Classic soil floors at Cancuén, Guatemala. *Journal of Archaeological Science*, **33**(5), 628–640.

Coronel, E. G., Bair, D. A., Brown, C. T., and Terry, R. E., 2014. Utility and limitations of portable X-ray fluorescence and field laboratory conditions on the geochemical analysis of soils and floors at areas of known human activities. *Soil Science*, **179**(5), 258–271.

Dempsey, E. C., 2014. *Trip Report, Archeological Investigations at Badlands National Park*. Manuscript on file, Lincoln, NB: National Park Service, Midwest Archeological Center.

Dibble, H. L., Chase, P. G., McPherron, S. P., and Tuffreau, A., 1997. Testing the reality of a "living floor" with archaeological data. *American Antiquity*, **62**(4), 629–651.

Dirix, K., Muchez, P., Degryse, P., Kaptijn, E., Mušič, B., Vassilieva, E., and Poblome, J., 2013. Multi-element soil prospection aiding geophysical and archaeological survey on an archaeological site in suburban Sagalassos (SW-Turkey). *Journal of Archaeological Science*, **40**(7), 2961–2970.

Dunning, N. P., McCane, C., Swinney, T., Purtill, M., Sparks, J., Mann, A., McCool, J.-P., and Ivenso, C., 2015. Geoarchaeological investigations in Mesoamerica move into the 21st century: a review. *Geoarchaeology*, **30**(3), 167–199.

Eden, M. J., Bray, W., Herrera, L., and McEwan, C., 1984. Terra Preta soils and their archaeological context in the Caqueta basin of southeast Colombia. *American Antiquity*, **49**(1), 125–140.

Farrand, W. R., 2001. Archaeological sediments in rockshelters and caves. In Stein, J. K., and Farrand, W. R. (eds.), *Sediments in Archaeological Context*. Salt Lake City: The University of Utah Press, pp. 29–66.

Feibel, C. S., 2001. Archaeological sediments in lake margin environments. In Stein, J. K., and Farrand, W. R. (eds.), *Sediments in Archaeological Context*. Salt Lake City: The University of Utah Press, pp. 127–148.

Fernández, F. G., Terry, R. E., Inomata, T., and Eberl, M., 2002. An ethnoarchaeological study of chemical residues in the floors and soils of Q'eqchi' Maya houses at Las Pozas, Guatemala. *Geoarchaeology*, **17**(6), 487–519.

Gaffney, C. F., and Gater, J., 2003. *Revealing the Buried Past: Geophysics for Archaeologists*. Stroud, UK: Tempus.

Glaser, B., and Woods, W. I., 2004. *Amazonian Dark Earths: Explorations in Space and Time*. Berlin: Springer.

Goldberg, P., and Bar-Yosef, O., 1998. Site formation processes in Kebara and Hayonim Caves and their significance in Levantine prehistoric caves. In Akazawa, T., Aoki, K., and Bar-Yosef, O. (eds.), *Neanderthals and Modern Humans in Western Asia*. New York: Plenum, pp. 107–125.

Goldberg, P., and Macphail, R. I., 2006. *Practical and Theoretical Geoarchaeology*. Malden, MA: Blackwell Publishing.

Goldberg, P., and Mandel, R. D., 2008. Caves and rockshelters. In Pearsall, D. M. (ed.), *Encyclopedia of Archaeology*. San Diego: Elsevier/Academic Press, Vol. 2, pp. 966–974.

Hajic, E. R., Mandel, R. D., Ray, J. H., and Lopinot, N. H., 2007. Geoarchaeology of stratified Paleoindian deposits at the Big Eddy site, southwestern Missouri, U.S.A. *Geoarchaeology*, **22**(8), 891–934.

Hannus, L. A., Winham, R. P., Cassells, E. S., Lueck, E. J., Palmer, L., Rossum, L., and Winham, K., 2003. *The Archeology of Badlands National Park, South Dakota*. Archeological Contract Series No. 175. Sioux Falls, SD: Archeology Laboratory, Augustana College.

Haslam, R., and Tibbett, M., 2004. Sampling and analyzing metals in soils for archaeological prospection: a critique. *Geoarchaeology*, **19**(8), 731–751.

Hutson, S. R., Magnoni, A., Beach, T., Terry, R. E., Dahlin, B. H., and Schabel, M. J., 2009. Phosphate fractionation and spatial patterning in ancient ruins: a case study from Yucatan. *Catena*, **78**(3), 260–269.

Kvamme, K. L., 2001. Current practices in archaeogeophysics: magnetics, resistivity, conductivity, and ground-penetrating radar. In Goldberg, P., Holliday, V. T., and Ferring, C. R. (eds.), *Earth Sciences and Archaeology*. New York: Kluwer Academic/Plenum Publishers, pp. 353–384.

Linderholm, J., 2007. Soil chemical surveying: a path to a deeper understanding of prehistoric sites and societies in Sweden. *Geoarchaeology*, **22**(4), 417–438.

Luzzadder-Beach, S., Beach, T., Terry, R. E., and Doctor, K. Z., 2011. Elemental prospecting and geoarchaeology in Turkey and Mexico. *Catena*, **85**(2), 119–129.

Macphail, R. I., 2002. *Pevensey Castle: Soil Micromorphology and Chemistry of the Roman Deposits and 'Dark Earth'*. Reading, UK: University of Reading.

Macphail, R. I., and Courty, M.-A., 1985. Interpretation and significance of urban deposits. In Edgren, T., and Jungner, H. (eds.), *Proceedings of the Third Nordic Conference on the Application of Scientific Methods in Archaeology, Mariehamn, Åland, Finland, 8–11 October 1984*. Helsinki: The Finnish Antiquarian Society, pp. 71–83.

Mandel, R. D., Arpin, T., Goldberg, P., and Bettis, E. A., III, 2006. Geomorphological investigation. In Thompson, J. B. (ed.), *Phase III Archaeological Data Recovery from the McNeal Fan (13MC15), Eisele's Hill Locality, Muscatine County, Iowa*. Cresco, IA: Bear Creek Archaeology, Inc.. BCA Report No 629, pp. 9–25.

Mandel, R. D., Jacob, J. S., and Nordt, L. C., 2007. Geoarchaeology of the Richard Beene site. In Thoms, A. V., and Mandel, R. D. (eds.), *Archaeological and Paleoecological Investigations at the Richard Beene Site (41BX831), South Central Texas*. College Station, TX: Texas A&M University. Center for Ecological Archaeology, Reports of Investigations No. 8, pp. 27–60.

Mandel, R. D., Murphy, L. R., and Mitchell, M. D., 2014. Geoarchaeology and paleoenvironmental context of the Beacon Island site, an Agate Basin (Paleoindian) bison kill in northwestern North Dakota, USA. *Quaternary International*, **342**, 91–113.

Marean, C. W., Goldberg, P., Avery, G., Grine, F. E., and Klein, R. G., 2000. Middle stone age stratigraphy and excavations at Die Kelders Cave 1 (Western Cape Province, South Africa): The 1992, 1993, and 1995 field seasons. *Journal of Human Evolution*, **38**(1), 7–42.

McCann, J. M., Woods, W. I., and Meyer, D. W., 2001. Organic matter and anthrosols in Amazonia: interpreting the Amerindian legacy. In Rees, R. M., Ball, B. C., Campbell, C. D., and Watson, C. A. (eds.), *Sustainable Management of Soil Organic Matter*. Wallingford, UK: CAB International, pp. 180–189.

Meignen, L., Bar-Yosef, O., and Goldberg, P., 1989. Les structures de combustion moustériennes de la grotte de Kébara (Mont Carmel, Israël). In Olive, M., and Taborin, Y. (eds.), *Nature et fonction des foyers préhistoriques: Actes du Colloque international de Nemours, 12-13-14 mai 1987*. France: APRAIF (Association pour la promotion de la recherche archéologique en Ile-de-France). Mémoires du Musée de Préhistoire d'Ile de France 2. Nemours, pp. 141–146.

Meignen, L., Bar-Yosef, O., Goldberg, P., and Weiner, S., 2001. Le feu au Paléolithique moyen: Recherches sur les structures de combustion et le statut des foyers. L'exemple du Proche-Orient. *Paléorient*, **26**(2), 9–22.

Neves, E. G., Petersen, J. B., Bartone, R. N., and Da Silva, C. A., 2003. Historical and socio-cultural origins of Amazonian dark earths. In Lehmann, J., Kern, D. C., Glaser, B., and Woods, W. I. (eds.), *Amazonian Dark Earths: Origin,* *Properties, Management*. Dordrecht: Kluwer Academic Publishers, pp. 29–50.

Parnell, J. J., Terry, R. E., and Nelson, Z., 2002. Soil chemical analysis applied as an interpretive tool for ancient human activities in Piedras Negras, Guatemala. *Journal of Archaeological Science*, **29**(4), 379–404.

Sánchez Vizcaíno, A., and Cañabate, M. L., 1999. Identification of activity areas by soil phosphorus and organic matter analysis in two rooms of the Iberian sanctuary "Cerro El Pajarrillo.". *Geoarchaeology*, **14**(1), 47–62.

Schlezinger, D. R., and Howes, B. L., 2000. Organic phosphorus and elemental ratios as indicators of prehistoric human occupation. *Journal of Archaeological Science*, **27**(6), 479–492.

Singer, R., and Wymer, J., 1982. *The Middle Stone Age at Klasies River Mouth in South Africa*. Chicago: University of Chicago Press.

Terry, R. E., Fernández, F. G., Parnell, J. J., and Inomata, T., 2004. The story in the floors: chemical signatures of ancient and modern Maya activities at Aguateca, Guatemala. *Journal of Archaeological Science*, **31**(9), 1237–1250.

Thompson, V. D., Arnold, P. J., III, Pluckhahn, T. J., and Vanderwarker, A. M., 2011. Situating remote sensing in anthropological archaeology. *Archaeological Prospection*, **18**(3), 195–213.

Thoms, A. V., and Mandel, R. D. (eds.), 2007. *Archaeological and Paleoecological Investigations at the Richard Beene Site (41BX831), South Central Texas*. Center for Ecological Archaeology, Reports of Investigations No. 8. College Station, TX: Texas A&M University.

Tiessen, H. (ed.), 1995. *Phosphorus in the Global Environment: Transfers, Cycles and Management*. New York: Wiley.

Venter, M. L., Thompson, V. D., Reynolds, M. D., and Waggoner, J. C., Jr., 2006. Integrating shallow geophysical survey: Archaeological investigations at Totógal in the Sierra de los Tuxtlas, Veracruz, México. *Journal of Archaeological Science*, **33**(6), 767–777.

Wells, E. C., and Terry, R. E., 2007. Introduction to the special issue: advances in geoarchaeological approaches to anthrosol chemistry, Part II: activity area analysis. *Geoachaeology*, **22**(4), 387–390.

Woods, W. I., and McCann, J. M., 1999. The anthropogenic origin and persistence of Amazonian dark earths. *Yearbook. Conference of Latin American Geographers*, **25**, 7–14.

Yule, B., 1990. The 'dark earth' and late Roman London. *Antiquity*, **64**(244), 620–628.

Cross-references

Anthrosols
Magnetometry for Archaeology
Soil Micromorphology
Soils

LOESSIC PALEOLITHIC, TAJIKISTAN

Richard S. Davis[1] and Vance T. Holliday[2]
[1]Department of Anthropology, Bryn Mawr College, Bryn Mawr, PA, USA
[2]Anthropology and Departments Geosciences, University of Arizona, Tucson, AZ, USA

The thick, extensive loess deposits of Europe and Asia contain buried evidence of Paleolithic occupations, and the relative ubiquity of archaeological remains spanning hundreds of thousands of years, within the loess of China, Tajikistan, Ukraine, the Czech Republic, and Germany, gave rise to the term "Loessic Paleolithic" (Ranov, 1995). The southern Tajik loess has the longest and most complete archaeological sequence; it is 100–200 m in thickness and contains multiple, well-expressed buried soils (Table 1) (Dodonov, 1991; Dodonov and Baiguzina, 1995; Dodonov, 2002). Artifacts are almost exclusively associated with the buried soils, which may have developed due to prolonged landscape stability, more hospitable interglacial climatic conditions, or some combination. The cycles of loess sedimentation and stability/soil formation provide insights into paleoenvironmental conditions and changes. Correlating buried soils between archaeological sites is key for establishing a cultural chronology.

Beginning in the 1970s, more than 40 archaeological discoveries have been made in the southern Tajik loess deposits. Virtually all the finds come from the buried soil pedocomplexes (PCs) that are correlated with the relatively warm, humid climates characteristic of interglacial periods. Principal artifact horizons are from the 12th, 11th, 6th, 5th, 4th, and 2nd PCs (lower to upper) (Table 1). Kul'dara, Karatau, Lakhuti, Obi-Mazar, and Khonako III are the chief localities where excavations have taken place and substantial collections recovered (Dodonov et al., 1992; Davis and Ranov, 1999; Dodonov, 2002). Kul'dara features a diminutive pebble flake industry located in the 11th and 12th PC, which lie below the Brunhes/Matuyama paleomagnetic boundary (~780,000 years B.P.) and are estimated to be ~800,000 years old (Table 1). Somewhat more discrete concentrations of artifacts were found within the 6th PC at Karatau I (~200,000 years ago based on thermoluminescence) and in the 5th PC at Lakhuti I (~130,000 years based on thermoluminescence) (Lomov and Ranov, 1984, 1985; Dodonov, 1991; Ranov, 1995). The TL ages may be underestimated according to Frechen and Dodonov (1998). Recent analysis has focused on correlating the PCs with marine ^{18}O stages, which would put Lakhuti and Karatau between 400 and 600 ka (Shackleton et al., 1995; Akhmetyev et al., 2005). The assemblages from both Karatau and Lakhuti also represent pebble tool industries, but they include choppers and large flake tools. The Khonako III site contains a blade industry identified as Middle Paleolithic with an estimated date of 200,000–240,000 years ago.

With the exception of Khonako III, the artifacts at all of the sites were not in concentrated horizons or clear occupational layers. They were instead distributed as if in a "suspension" (Ranov and Schäfer, 2000). At Kul'dara, for example, the density of lithic artifacts averaged less than 3 per cubic meter, and they were distributed vertically over a depth of 1.8 m (Davis and Ranov, 1999, p. 188). This highlights a problematic aspect of the "Loessic

Loessic Paleolithic, Tajikistan, Table 1 Stratigraphy of the "Loess Paleolithic" in southern Tajikistan[a]

			Pebble Tradition		*Blade Tradition*		
	Soil Number	**Soil Type**[b]	**Sites**	**Industries**	**Mousterian & Upper Paleolithic Sites in Caves & Open Air**		**China Paleolithic**
	1	Serozem (Orthent? Cambid?)			Tutkaul III Shougnou I	Upper Paleolithic	
	2	Lt. Cinnamon (Ustochrept)			Shougnou II Shougnou III Shougnou IV		Shuidonggou (32–40 ka)
	3	Lt. Cinnamon (Ustochrept)	Khonako II (?)	Flake debris pebble-tool technology			
	4	Brown (Inceptisol? Alfisol?)	Lakhuti III	Non clear with crude flakes, debris, pebble-tool technology	Khudji Kara-Bura Ogzi-Kichik	Mousterian	
	5	Brown (Inceptisol? Alfisol?)	Lakhuti I	Evolved local pebble tool-technology with a few Levallois elements			Xuijiayao (100 ka)
	6	Brown (Inceptisol? Alfisol?)	Karatau I	Local pebble tool-technology without systematic flaking			Zhoukoudian 1–3 (230 ka)
	7	Brown (Inceptisol? Alfisol?)					
	8	Brown (Inceptisol? Alfisol?)					
B	9						
M	10						
	11		Kul'dara	Short flakes, pebble-techniques without choppers			Donguttuo (1 Ma)
	12						

[a]Modified from Ranov (1995:Table 1). BM indicates position of the Brunhes-Matuyama magnetostratigraphic boundary (~780 ka).

[b]Soil type listed by Ranov (1995:Table 1) is indicated, plus likely Soil Taxonomy equivalent in parentheses.

Paleolithic" archaeology in Tajikistan and elsewhere. The pedocomplexes are 2–4 m thick, and archaeological features such as hearths, pits, or activity areas are absent. Only occasional faunal fragments have been found. The zones of maximum artifact concentration are in association with the zones of maximum pedogenic expression, but no discrete occupation levels are apparent. One interpretation is that there was repeated occupation of the sites during slow aggradation of the soils (Lomov and Ranov, 1984, 1985). This could well be the case on a loess landscape, as described in the model of soil upbuilding (Kemp, 2001). Turbation cannot be discounted as a cause, however. In comparing the vertical distribution of artifacts at Lakhuti, Karatau, and Kul'dara, the youngest site (Lakhuti) has the most discrete concentration, while the oldest site (Kul'dara) has the least discrete concentration (see Lomov and Ranov, 1985, Figures 30–77; or Holliday, 2004, Figure 6.19).

The Tajik loess finds are highly significant discoveries. They were the first Lower and Middle Pleistocene Paleolithic sites found in good stratigraphic context, and they documented an adaptation of early populations to a semiarid interglacial environment within Central Asia.

Bibliography

Akhmetyev, M. A., Dodonov, A. E., Somikova, M. V., Spasskaya, I. I., Kremenetsy, K. V., and Klimanov, V. A., 2005. Kazakhstan and Central Asia (plains and foothills). In Velichko, A. A., and Nechaev, V. P. (eds.), *Cenozoic Climatic and Environmental Changes in Russia*. Boulder: Geological Society of America. Geological Society of America Special Paper, Vol. 382, pp. 139–161.

Davis, R. S., and Ranov, V. A., 1999. Recent work on the Paleolithic of Central Asia. *Evolutionary Anthropology*, **8**(5), 186–193.

Dodonov, A. E., 1991. Loess of Central Asia. *GeoJournal*, **24**(2), 185–194.

Dodonov, A. E., 2002. *Chetvertichnyi Period Srednei Azii: Stratigrafi͡ia, korreli͡at͡sii͡a, paleografiia [Quaternary of Middle Asia: Stratigraphy, Correlation, Paleogeography]*. Moscow: GEOS. Trudy, Geologicheskii institut, Rossiiskaia akademiia nauk, Vol. 546. Transactions of the Geological Institute of the Russian Academy of Sciences.

Dodonov, A. E., and Baiguzina, L. L., 1995. Loess stratigraphy of Central Asia: Palaeoclimatic and palaeoenvironmental aspects. *Quaternary Science Reviews*, **14**(7–8), 707–720.

Dodonov, A. E., Ranow, V. A., and Schäfer, J., 1992. *Das Lößpaläolithikum am Obi-Mazar (Tadschikistan) [The Loess Paleolithic on the Obi-Mazar (Tajikistan)]*. Mainz: Forschungsinstitut für Vor- und Frühgeschichte, Römisch-Germanisches Zentralmuseum. Jarhrbuch des Römisch-Germanischen Zentralmuseums, Vol. 39, pp. 209–243.

Frechen, M., and Dodonov, A. E., 1998. Loess chronology of the middle and upper Pleistocene in Tadjikistan. *Geologische Rundschau*, **87**(1), 2–20.

Holliday, V. T., 2004. *Soils in Archaeological Research*. New York: Oxford University Press.

Kemp, R. A., 2001. Pedogenic modification of loess: significance for palaeoclimatic reconstructions. *Earth-Science Reviews*, **54**(1–3), 145–156.

Lomov, S. P., and Ranov, V. A., 1984. Distribution of Palaeolithic tools in the buried soils of Tadzhikistan. *Soviet Soil Science*, **16**(2), 18–28.

Lomov, S. P., and Ranov, V. A., 1985. The peculiarities of the Pleistocene palaeosol formations and distribution of embedded Palaeolithic tools. In Agrawal, D. P., Kusumgar, S., and Krishnamurthy, R. V. (eds.), *Climate and Geology of Kashmir, the Last 4 Million Years: Proceedings of the International Workshop on the Late Cenozoic Palaeoclimatic Changes in Kashmir and Central Asia, Ahmedabad, 19–23 October 1982*. New Delhi: Today and Tomorrows Printers and Publishers. Current Trends in Geology, Vol. 6, pp. 227–240.

Ranov, V., 1995. The "Loessic Palaeolithic" in south Tadjikistan, Central Asia: its industries, chronology and correlation. *Quaternary Science Reviews*, **14**(7–8), 731–745.

Ranov, V., and Schäfer, J., 2000. Loessic Paleolithic. *Archaeology Ethnology and Anthropology of Eurasia*, **2**(2), 20–32.

Shackleton, N. J., An, Z., Dodonov, A. E., Gavin, J., Kukla, G. J., Ranov, V., and Zhou, L. P., 1995. Accumulation rate of loess in Tadjikistan and China: relationship with global ice volume cycles. *Quaternary Proceedings*, **4**, 1–6.

Cross-references

Eolian Settings: Loess
Paleoenvironmental Reconstruction

LUMINESCENCE DATING OF POTTERY AND BRICKS

Ian K. Bailiff
Department of Archaeology, University of Durham, Durham, UK

Definition

The luminescence dating of ceramic materials, including pottery and bricks, is an experimental method for determining the time elapsed in years since the ceramic material was produced by firing in a kiln.

Introduction

Luminescence techniques for dating ceramic artifacts have been described in detail by Aitken (1985, 1998), and guidelines produced by English Heritage (Duller, 2008) provide a concise overview of applying the method. Although the dating of sedimentary deposits currently forms the main focus of application for luminescence dating in general, the dating of ceramics is discussed here and in a number of review papers (Feathers, 2003; Preusser et al., 2008; Wintle, 2008; Liritzis et al., 2013), and also by Wagner (1998).

Historical perspective

When thermoluminescence (TL) dating was proposed as a new scientific dating method in the 1960s (Aitken, 1985; Wintle, 2008), its viability was demonstrated using pottery from archaeological contexts, objects that had been heated in the course of their production. Application to other types of ceramic artifacts, such as curated works of art (Fleming, 1979), and ceramic building materials (CBMs) soon followed. During the 1980s the development of optically stimulated luminescence (OSL) techniques led to a focusing of research effort on the dating of processes associated with sedimentary deposits that had not been heated above ambient temperatures, and this type of application now dominates the field. Both TL and OSL measurement techniques can be applied to date ceramic materials, but the use of OSL tends to be preferred by dating laboratories.

Although testing of the earliest pottery of Late Pleistocene origin is within the chronological range of the method (Kuzmin et al., 2001), its adoption for dating pottery was muted, despite the common occurrence of pottery on many sites from the Neolithic onwards (Orton et al., 1993). For general application, the specialist advice needed for sampling made its deployment less convenient compared with radiocarbon testing, and, moreover, the levels of uncertainty in luminescence dates were considered too high to improve upon pottery chronologies developed on the basis of typology and fabric analysis. Since the dating of many sites of late prehistory has relied on the use of typologies and other visual characteristics, there is an interest in testing the robustness of such pottery chronologies by applying absolute dating methods. In cases where the application of radiocarbon is not appropriate, either because of poor temporal resolution arising from calibration issues or where no suitable organic samples are available, there is consequently a potential role for luminescence to serve in the testing of pottery chronologies. In addition, the dating of brick in standing buildings and monuments lacking diagnostic features has, after years of dormancy, become an active area of research.

Technical issues

The clock mechanism that forms the basis of luminescence dating employs the buildup of electric charges (e.g., electrons) stored in "traps" that are associated with imperfections within the structure of crystalline grains of luminescent minerals (e.g., quartz and feldspars). Ionizing radiation emitted by naturally occurring radioactive sources present within ceramic and environmental materials (e.g., soils forming the burial medium) penetrates the mineral grains, causing the generation of free electric charges within the grains. Some of the electrons removed from their orbitals by the radiation are captured and stored in the traps, and over time, the energy absorbed by the grains during this process is defined as the "absorbed dose." The population of trapped charges increases with time until it is released by heat stimulation of the grains in the laboratory, producing luminescence. In simple terms, the intensity of the luminescence emitted is proportional to the time elapsed since a "zeroing" process. For ceramic materials, heating to firing temperatures represents that zeroing because it removes all previously stored charges, resetting the clock mechanism, and, upon cooling to ambient temperatures, the accumulation of trapped charges resumes. The (steady) rate at which the population of stored charges increases with time is proportional to the dose rate, which is related to the concentration of radioactive sources within the ceramic and in the surrounding burial medium. These concentrations vary according to the geological source of the material.

The luminescence age equation (Aitken, 1985, 1998), expressed in its most compact form,

$$\text{Age} = \text{Paleodose/Dose Rate},$$

is used to calculate the time elapsed since the zeroing process. The age, given in years before the year of testing, is accompanied by an overall uncertainty, given at the 68 % level of confidence (1σ), that is, typically between ±5 % and ±10 % of the age. The paleodose, determined by applying luminescence techniques (these are discussed in Duller, 2008) to grains extracted from the dating sample, corresponds to the cumulative absorbed dose (in units of gray, Gy) received by the grains following a zeroing process, such as a kiln firing in the case of a ceramic. Since resetting can be achieved at temperatures as low as ca. 400 °C (i.e., baked or burnt clay), most well-fired archaeological pottery will have met this condition. Within the relatively short lifetime of a cooking pot, the effect of reheating on a fire has a negligible effect on the luminescence age, but if sherds were redeposited onto a ground surface long after burial and subjected to prolonged heating during a conflagration to temperatures in excess of those indicated above, resetting would occur and a date for the destruction event obtained, not the original kiln firing. The value of paleodose inserted into the age equation is obtained by calculating the average of the results obtained from many individual samples of grains, making the experimental work a lengthy process. The dose rate is usually determined by measuring the concentration of radionuclides present in the sample and the surrounding burial medium and then applying conversion factors (Aitken, 1985, 1998).

Paleodose

Most ceramic materials contain grains of luminescent minerals, such as quartz and feldspar, within the fine (e.g., <20 μm diameter) or coarse (e.g., 100–300 μm diameter) fractions of clays and temper, respectively. Such grains can be extracted in the laboratory by mechanical crushing and sieving and the application of acid treatments. Typically, a minimum of 25 g of ceramic is sufficient for dating measurements, although for some applications this can be reduced significantly by drilling (Fleming, 1979). There are important differences in the luminescence properties of the two commonly present mineral types, quartz and feldspar, and this affects their use for dating measurements. In particular, trapped charge, which forms the basis of the chronometer mechanism, is retained without significant loss in quartz over archaeological timescales, whereas for most feldspars, there is a small but continuous loss due to a physical effect referred to as anomalous fading that causes the age to be underestimated. Although a correction can be applied for the loss, this increases the uncertainty in the luminescence age, and each sample must be tested to establish the extent of fading, since the rate of loss varies according to the geological source of the feldspar (Lamothe, 2004). Hence, coarse quartz grains are usually preferred when testing ceramic materials, providing they are present in the fabric. Where this is not the case, extraction of the "fine-grain" fraction that usually contains both quartz and feldspar provides an alternative approach. Although feldspars can be selectively removed using acid treatment, the fine-grain technique for paleodose determination tends to be applied routinely without such additional treatment unless part of a methodological study.

Dose rate

There are two physical volumes of interest when assessing the dose rate to grains extracted from a sample to be dated: (a) the ceramic sample itself and (b) its immediate environment. The latter comprises the burial medium (to a distance of about 50 cm; Aitken, 1985) which contains radionuclides emitting gamma rays contributing ca. 25–45 % of the dose rate, where the proportion depends on the grain size selected for paleodose measurements. Hence an assessment of the radionuclide content of both the ceramic artifact and the immediate environment is required. The assessment of the dose rate is more complex for samples adjacent to layers of media with differing radionuclide composition or within deposits near the ground surface, for example, and for this reason the longstanding advice given (Aitken, 1985) in the case of excavated pottery has been to select samples located within a uniform burial medium. Given that much of the burial medium of interest may have been removed during excavation, this technically sound sampling advice has persisted (Duller, 2008). For more complex situations, such as shallow or surface contexts, laboratories may use the fine-grain fraction for paleodose determination because a higher proportion (ca. 75 %) of the dose rate is due to radioactive sources located within the pottery, and this demonstrates that the composition of the burial medium and the extent of overburden exert somewhat less influence on the luminescence age. In the case of a brick within the external wall of a standing building, the immediate environment, as referred to above, includes the surrounding bricks and the ground adjacent to the wall (e.g., soil); in this instance, a sample location having the simplest environment is usually preferred.

A further factor that has a bearing on sampling is the moisture content of both ceramic and the burial medium because water has a moderating effect on the dose rate. An average value for the moisture content during the burial period is estimated by the laboratory, and a conservative allowance is usually made for the uncertainty (typically ± 20 %) in the value adopted. Although the maximum moisture uptake of the ceramic, which is controlled by the porosity of the fabric, can be measured in the laboratory, it is desirable to obtain samples of both pottery and soil and store them so as to retain the moisture content representative of contemporary conditions within the burial environment. The overall precision in the luminescence age increases (i.e., the uncertainty is lower) in regions where there has been long-term aridity, but it decreases where the pottery is porous and the moisture content relatively high.

Luminescence age

There is no internationally agreed specification for the presentation of luminescence dating results, but a listing of technical parameters related to the evaluation of the paleodose and the dose rate normally accompany the luminescence age in publications and formal reports. The Ancient TL Date List, although no longer actively compiled, provided a systematic compilation of dating results, and the last two issues produced included listings of luminescence dates for pottery from Britain (Barnett, 1999) and the Southwest of North America (Feathers, 2000); more recent guidance concerning aspects of date quotation is included in Duller (2008).

Pottery

Applications of the method to dating pottery can be broadly grouped into those that (a) establish the date of deposition for a layer or feature from which the pottery was recovered, (b) test chronologies developed through pottery typologies, and (c) examine methodological issues, such as the feasibility of dating a previously untested type of pottery. There are several published large-scale dating studies, where the term "large scale" applied here refers to several tens of determinations rather than the several hundreds that could be envisaged with radiocarbon.

The accuracy of luminescence has been tested against independent dating evidence with pottery recovered from sealed contexts where its use before deposition was judged to be short-lived. From a statistical analysis of the results for 24 sherds of diagnostic pottery of the British Iron Age (first millennium BC), an average difference of $\sim$100 years was obtained between the luminescence dates and the midpoint of the assigned age range in each case (Barnett, 2000). Similarly, comparisons of luminescence dates for pottery from short-lived Navajo sites of ca. AD 1700 in North America with independent dating evidence provided by dendrochronology produced a favorable outcome (Feathers, 2000, 2003).

On many sites, pottery is frequently undiagnostic and found scattered both spatially and temporally within the stratigraphy. Following fragmentation and discard, sherds may be redeposited in the filling of large features such as ditches, pits, and middens. Luminescence dating of pottery from sites in Britain and North America has confirmed that indiscriminate testing of redeposited pottery in large features will produce misleading results when the processes of manufacture and deposition are significantly displaced in time. However, luminescence has a constructive role to play by providing a means of testing chronologies for the onset and persistence of particular fabric types. The luminescence dates obtained in several studies on pottery from sites in Britain (Barnett, 2000; Cramp, 2006) and North America (Feathers, 2009) have challenged aspects of previously established fabric chronologies. In one region of Britain (Northampton), the incorporation of fine or coarse shell fragments in temper had been used to distinguish Early and Late Iron Age manufacture, corresponding to a separation of several hundred years, yet the luminescence dates showed that each type of temper was not confined to one of these periods and that the two groups strongly overlapped. In related work, the luminescence dates obtained for sherds of scored ware thought to have been introduced during the fourth century BC suggest much earlier introduction, in the ninth century BC. Comparable issues have been raised by the testing of shell-tempered pottery from North American native sites in the Lower Mississippi Valley (Feathers, 2009) and also sand-tempered fabrics from sites in southern Florida (Feathers, 2003). While the majority of luminescence dates obtained for shell-tempered pottery from two mound sites were consistent with the assigned date range in the early eleventh century AD on the basis of the cultural assemblage and radiocarbon dates, luminescence dates of up to nearly a millennium earlier were obtained for several sherds from each site. These early dates, although considered enigmatic, flagged the possibility that relict pottery may have been brought to the sites by migrants. AMS radiocarbon dating applied to the carbonate temper to cross-check the reliability of the luminescence dates has since indicated that further work is required to evaluate the extent of a reservoir offset correction to the radiocarbon ages (Peacock and Feathers, 2009). Resolution of this issue represents an important test of the capability of luminescence to provide a reliable tool for investigating the full temporal ranges of pottery chronologies. While this aspect is being more actively investigated for North American pottery, work has also progressed sporadically on various sites across Eurasia and East Asia.

Due to the nature of the native North American mound sites, pottery is sampled from contexts that are very shallow or within erosional surfaces. As indicated earlier, the fine-grain technique can be applied in such cases to reduce the uncertainty in the dose rate, albeit with the attendant issue of anomalous fading to deal with if the feldspar minerals are not removed. The further development of such work has wider methodological implications for sites in other parts of the world where pottery surface scatters form a key component of the surviving archaeological evidence (Dunnell and Feathers, 1994; Sampson et al., 1997) and where the testing of organic matter by radiocarbon is highly problematic because of postdepositional disturbance.

Ceramic building materials

The dating of ceramic building materials (CBM) is a natural extension of the dating of pottery in terms of the experimental techniques applied. Fired brick has been used extensively in the construction of buildings during the last two millennia, and although the literature is currently limited, examples of dating applications can be found for individual buildings and structures in Europe (e.g., the Czech Republic, Denmark, England, Finland, France, Germany, Italy, and Poland), in Asia (e.g., Cambodia, India, Sri Lanka, Thailand, and Uzbekistan), and in South America (Brazil). While precise dating of high-status buildings of the last millennium can be obtained to within a couple of decades or better, lower-status "vernacular" buildings of the Late Medieval and early modern periods in Europe are problematic; dating the construction and phasing of structural changes to better than 50–100 years are often difficult to achieve. In these circumstances, there is the opportunity for luminescence to make a contribution to the dating of brick buildings where an overall uncertainty in the date of ca. ± 5 % of the age (± 25 years for a 500-year old sample) can be approached. When applied to four buildings with reliable documentary and stylistic dating evidence in England, luminescence dating of brick produced extremely encouraging agreement (Bailiff, 2007): for six samples taken from these dating control buildings (within the range of ca. AD 1400–1720), the mean difference between the central values of luminescence and assigned ages was 5 ± 10 years (s.d., $n = 6$).

The value of applying an absolute dating method is illustrated by studies that address wider research questions of chronology that are not bound by regional typologies and also extend beyond application to a single building. For the period following the Roman withdrawal from northwestern Europe during the early fifth century AD, in particular from Britain and Gaul, there has been a longstanding uncertainty regarding when the manufacture of CBMs was resumed. Recent work with bricks from a group of ecclesiastical buildings in northwestern France (Blain et al., 2007) and England (Bailiff et al., 2010) indicates that, while in France the practice of brickmaking was maintained during the Early Medieval period, it did not resume until the eleventh century AD in England. The testing of brick from Late Medieval buildings in England has also provided an initially unexpected outcome. Whereas it had been assumed that new bricks were produced for a specific building, the dates obtained for multiple bricks from a single building suggest that recycling was practiced by late medieval builders. This is of particular interest to building historians when assessing changes to, and loss of, buildings in urban and rural landscapes. However, the possibility of recycling CBM also provides a note of caution when sampling: in addition to a structural examination of the phasing of a building, the brickwork requires careful inspection for the use of recycled brick. In response to this issue, the possibility of dating the emplacement, rather than manufacture, of bricks using OSL has been explored by testing luminescent grains located within either the surface of a brick (Vieillevigne et al., 2006) or incorporated in lime mortar (Goedicke, 2011), as long as the grains were sufficiently exposed to sunlight before use in construction and subsequently stored under dark conditions until tested in the laboratory.

Summary

After a prolonged period of gestation, two main methodological roles for the application of luminescence dating to archaeological ceramic materials have emerged: the building and testing of pottery fabric chronologies and dating the manufacture of ceramic building materials. When luminescence dates for pottery and brick have been compared against independent dating evidence in well-designed studies, the performance of the method has been found to be reliable and accurate within the estimated experimental uncertainties.

Bibliography

Aitken, M. J., 1985. *Thermoluminescence Dating*. London: Academic.

Aitken, M. J., 1998. *An Introduction to Optical Dating: The Dating of Quaternary Sediments by the Use of Photon-Stimulated Luminescence*. Oxford: Oxford University Press.

Bailiff, I. K., 2007. Methodological developments in the luminescence dating of brick from English late-medieval and post-medieval buildings. *Archaeometry*, **49**(4), 827–851.

Bailiff, I. K., Blain, S., Graves, C. P., Gurling, T., and Semple, S., 2010. Uses and recycling of brick in medieval and Tudor English buildings: insights from the application of luminescence dating and new avenues for further research. *The Archaeological Journal*, **167**(1), 165–196.

Barnett, S. M., 1999. Date list 6: luminescence dates for late bronze age and iron age pottery assemblages in eastern and northern Britain. *Ancient TL*, **17**(1), 23–40.

Barnett, S. M., 2000. Luminescence dating of pottery from later prehistoric Britain. *Archaeometry*, **42**(2), 431–457.

Blain, S., Guibert, P., Bouvier, A., Vieillevigne, E., Bechtel, F., Sapin, C., and Baylé, M., 2007. TL-dating applied to building archaeology: the case of the medieval church Notre-Dame-Sous-Terre (Mont-Saint-Michel, France). *Radiation Measurements*, **42**(9), 1483–1491.

Cramp, R. J., 2006. *Wearmouth and Jarrow Monastic Sites*. Swindon: English Heritage, Vol. II.

Duller, G. A. T., 2008. *Luminescence Dating: Guidelines on Using Luminescence Dating in Archaeology*. Swindon: English Heritage.

Dunnell, R. C., and Feathers, J. K., 1994. Thermoluminescence dating of surficial archaeological material. In Beck, C. (ed.), *Dating in Exposed and Surface Contexts*. Albuquerque: University of New Mexico Press, pp. 115–137.

Feathers, J. K., 2000. Date list 7: luminescence dates for prehistoric and protohistoric pottery from the American Southwest. *Ancient TL*, **18**(2), 51–61.

Feathers, J. K., 2003. Use of luminescence dating in archaeology. *Measurement Science and Technology*, **14**(9), 1493–1509.

Feathers, J. K., 2009. Problems of ceramic chronology in the southeast: does shell-tempered pottery appear earlier than we think? *American Antiquity*, **74**(1), 113–142.

Fleming, S. J., 1979. *Thermoluminescence Techniques in Archaeology*. Oxford: Clarendon Press.

Goedicke, C., 2011. Dating mortar by optically stimulated luminescence: a feasibility study. *Geochronometria*, **38**(1), 42–49.

Kuzmin, Y. V., Hall, S., Tite, M. S., Bailey, R., O'Malley, J. M., and Medvedev, V. E., 2001. Radiocarbon and thermoluminescence dating of the pottery from the early neolithic site of Gasya (Russian Far East): initial results. *Quaternary Science Reviews*, **20**(5–9), 945–948.

Lamothe, M., 2004. Optical dating of pottery, burnt stones, and sediments from selected Quebec archaeological sites. *Canadian Journal of Earth Sciences*, **41**(6), 659–667.

Liritzis, I., Singhvi, A. K., Feathers, J. K., Wagner, G. A., Kadereit, A., Zacharias, N., and Li, S.-H., 2013. *Luminescence Dating in Archaeology, Anthropology, and Geoarchaeology. An Overview*. Heidelberg: Springer.

Orton, C., Tyers, P., and Vince, A. G., 1993. *Pottery in Archaeology*. Cambridge: Cambridge University Press. Cambridge Manuals in Archaeology.

Peacock, E., and Feathers, J. K., 2009. Accelerator mass spectrometry radiocarbon dating of temper in shell-tempered ceramics: test cases from Mississippi, Southeastern United States. *American Antiquity*, **74**(2), 351–369.

Preusser, F., Degering, D., Fuchs, M., Hilgers, A., Kadereit, A., Klasen, N., Krbetschek, M., Richter, D., and Spencer, J. Q. G., 2008. Luminescence dating: basics, methods and applications. *Eiszeitalter und Gegenwart – Quaternary Science Journal*, **57** (1–2), 95–149.

Sampson, C. G., Bailiff, I., and Barnett, S., 1997. Thermoluminescence dates from later Stone Age pottery on surface sites in the Upper Karoo. *South African Archaeological Bulletin*, **52**(165), 38–42.

Vieillevigne, E., Guibert, P., Zuccarello, A. R., and Bechtel, F., 2006. The potential of optically stimulated luminescence for medieval building; a case study at Termez, Uzbekistan. *Radiation Measurements*, **41**(7), 991–994.

Wagner, G. A., 1998. *Age Determination of Young Rocks and Artifacts: Physical and Chemical Clocks in Quaternary Geology and Archaeology*. Berlin: Springer.

Wintle, A. G., 2008. Fifty years of luminescence dating. *Archaeometry*, **50**(2), 276–312.

Cross-references

Ceramics
Optically Stimulated Luminescence (OSL) Dating
Radiocarbon Dating

M

MAGNETOMETRY FOR ARCHAEOLOGY

Jörg W. E. Fassbinder
Ludwig–Maximilians University of Munich, Munich, Germany
Bayerisches Landesamt für Denkmalpflege, Munich, Germany

Synonyms

Magnetic prospecting

Definition

Magnetometry. Application of magnetometers to detect and trace archaeological features and structures that lie beneath the ground

Field magnetometers. Instrumentation adapted for magnetic prospection of near-surface structures in archaeology

Soil magnetism. Applying mineral magnetic analysis and methods of measuring rock magnetism to the characterization of the magnetic properties of soils

Introduction

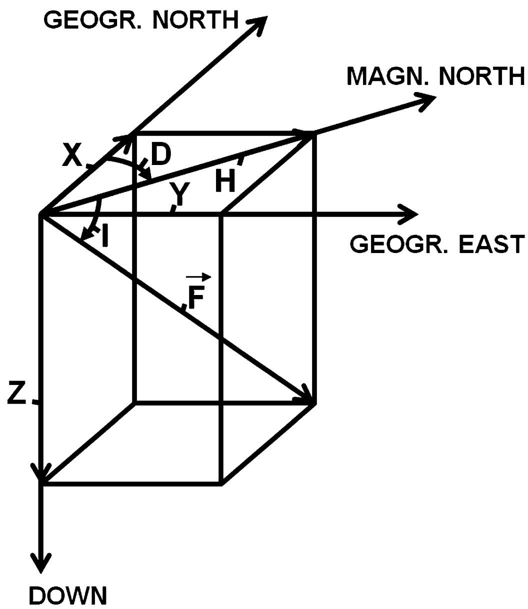
Magnetic prospection was applied for the first time to archaeology in 1956 (Belshé, 1957; Aitken, 1958), and over the years since then, it has become one of the most important archaeological methods for the detection and mapping of buried remains at large archaeological sites (Aitken, 1974; Scollar et al., 1990; Clark, 1996; Neubauer et al., 1998–1999; Benech, 2005; David et al., 2008). Magnetic detection methods are extremely sensitive in the characterization and analysis of iron oxides, much more so than any other form of chemical analysis. Therefore, given a full understanding of the nature of magnetic properties, many details of soil layers and buried archaeological structures can be discovered, visualized, and interpreted only by the "magnetic eye" (Schleifer et al., 2003; Fröhlich et al., 2003; Schleifer, 2004). A complete archaeological interpretation prior to excavation must consider all available archaeological background information as well as surface findings; however, many more crucial details can be derived through a comprehensive soil magnetic analysis, and many new archaeological questions arise from such geophysical prospecting results. For a long time, archaeologists held the firm conviction that geophysical prospecting results on their own would be only of limited use in the resolution of archaeological problems. Today, it has become commonplace that the initiation of a modern archaeological excavation must be preceded by some kind of geophysical prospecting (Schmidt, 2002; Fassbinder, 2007; Aspinal et al., 2008; Fassbinder, 2015a).

The great success of magnetic prospection in general is due to the fact that almost all soils of the world show an enhancement of magnetic minerals such as maghemite or magnetite in the topsoil (Le Borgne, 1955, 1960). Except for very rare situations, mostly on sites with dammed-up water and consistent soil wetness, there exist no limiting geological factors precluding the application of magnetic prospecting. Enrichment of these minerals in archaeological soil layers – especially in fireplaces, but also in ditches, pits, or postholes – is caused by the formation of these minerals either by natural or anthropogenic fires, varied pedogenic processes (Taylor et al., 1987), or magnetotactic soil bacteria (Fassbinder et al., 1990; Stanjek et al., 1994). The use of fire, however, plays the major role in the enhancement of magnetic minerals in soils, since this occurs on nearly all sites from the Paleolithic to modern times.

The magnetometer

There exists a wide range of suitable but very different instruments for the measurement of the Earth's magnetic

A.S. Gilbert (ed.), *Encyclopedia of Geoarchaeology*, DOI 10.1007/978-1-4020-4409-0,



Magnetometry for Archaeology, Figure 1 Common coordinate system representing the Earth's magnetic field. The declination angle between geographic (true) north and magnetic north is the declination (D). The inclination (I) is the magnetic dip, an angle that varies from place to place because the lines of force of the Earth's magnetic field do not generally run parallel to the ground surface. The intensity (F) of the field is proportional to the force it exerts on a magnet. Another common representation uses x- (north), y- (east), and z- (down) coordinates.

field (Lenz, 1990); however, for the special application of archaeological prospection, a robust but also sensitive instrument that can be operated easily and quickly in the field is required (Becker, 1995, 1997; Gaffney et al., 2000).

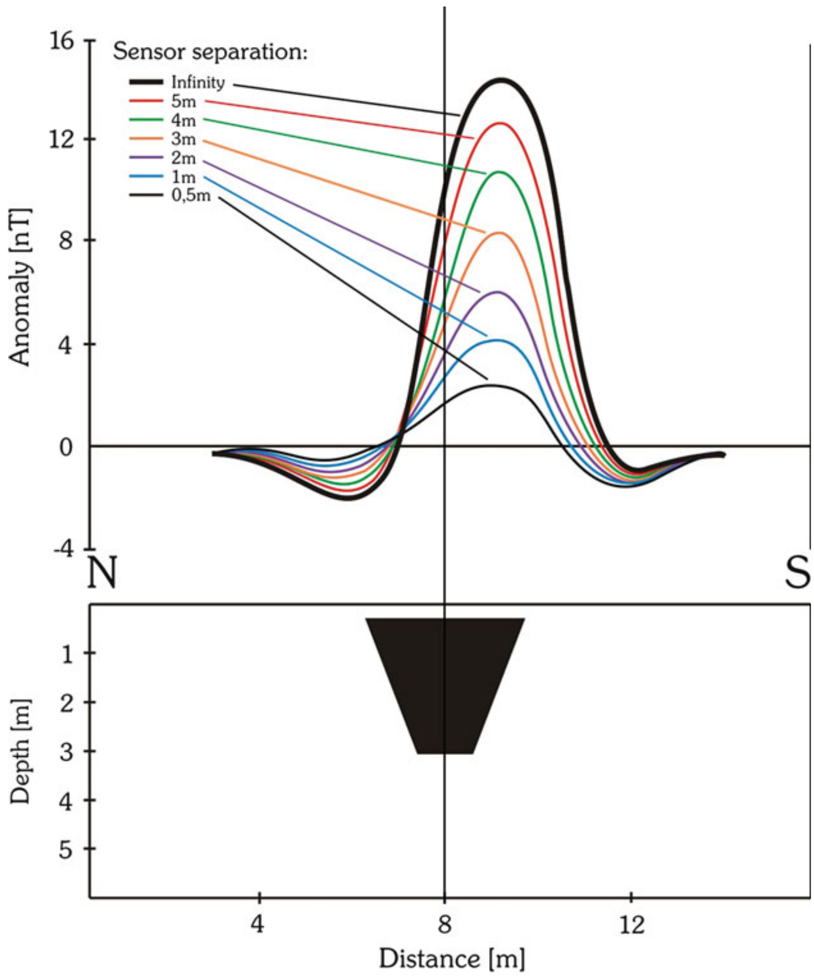
The survey procedure involves marking out the area to be surveyed as a grid of 20 × 20 m, 40 × 40 m, or other dimensions and then conducting the survey by measuring the magnetic field at discrete intervals, such as distances of 25 × 25 cm or 25 × 50 cm. Surveying on a grid requires walking along the guidelines to mark the profiles. The magnetometer probe can be carried by hand or mounted on a wheeled device ca. 30 cm above the ground. With the use of an integrated GPS, it is possible to eliminate the need to walk along the guidelines, but the survey still requires walking perfectly straight lines with a clipping radius of 25 cm to guarantee sufficient accuracy.

In general, one has to differentiate between *vector* and *scalar* magnetometers. While the vector magnetometer measures only the intensity of one direction (the x-, y-, or z-component) of the Earth's magnetic field, the scalar magnetometer measures the total intensity, F, of the Earth's magnetic field more or less independently of the orientation of the probe (see Figure 1).

The diurnal variations of the Earth's magnetic field are sometimes in the same range as those of the magnetic anomalies caused by buried archaeological remains. These diurnal disturbances are removed automatically with vector magnetometers since they are designed as gradiometers and can be operated in the field in a gradiometer mode only – where the device measures the gradient z-component of the Earth's magnetic field (determined by two fluxgate sensors that are mechanically fixed within a single device). In theory, and in the laboratory, one could design such a device with any arbitrary intersensor distance, but in practice it is difficult to design such a mechanically stable instrument with a nonmagnetic distance. Commercial fluxgate magnetometers are available with gradients of 50–100 cm. Scalar magnetometers are more or less tolerant of tilting sensors and can be applied as a differential or as a variometer system – where the device measures the difference in magnetic field between two places at the surface using adjacent sensors and thus with gradients greater than 5 m. Otherwise, the resulting data need complex treatment in order to remove the effects of these daily variations.

The decision to use a particular magnetometer system should be carefully balanced between the advantages and disadvantages of each system, and this will depend very much on the situation and the specific aim of the survey. Vector magnetometers that are designed for the measurement of the z-component (vertical) are quite independent of disturbances in the x-y horizontal components. Hence, these instruments can be more easily operated in the vicinity of a magnetic vehicle or nearby technical installations (e.g., metal structures, brick buildings, etc.) that would interfere with the measurement of subsurface variations. On the other hand, instrument sensitivity is limited by other factors, namely, the need to use a gradiometer system. Although SQUID magnetometers (superconducting quantum interference devices with sensitivity of the tensor component ±1 femtotesla or 10^{-15} T) are physically the most sensitive instruments, in practice (like other vector magnetometers), they can operate only in a gradiometer mode (Chwala et al., 2001; Schultze et al., 2007). While fluxgate magnetometers operate with a separation of 50–100 cm, SQUIDs are restricted by other physical reasons to a sensor separation of 4 cm.

Modern total field instruments like the proton magnetometer, the Overhauser magnetometer, or the optically pumped alkali-vapor magnetometer such as cesium magnetometers have a sensitivity of ±0.1 picotesla (10^{-12} T), but they can be operated in a "variometer" or "duo-sensor" configuration and therefore reach an overall sensitivity that is in the same range as the SQUIDs (Lenz, 1990; Becker, 1995, 1997). In this differential configuration, the reference probe is set virtually to infinity, and therefore all magnetic anomalies will be detected with their maximum intensity (Figure 2). The advantage is that the resulting image gives more information at greater depths (ca. 1–3 m), while fluxgate gradiometer results



Magnetometry for Archaeology, Figure 2 Dependence of the intensity of a magnetic anomaly above a V-shaped ditch (about 2.75 m deep and 3.5 m wide at the top) on the sensor/probe configuration of a magnetometer calculated for an inclination of the Earth's magnetic field of 60° in the northern hemisphere.

show archaeological structures more sharply, since they may be limited to the first meter beneath the surface by their gradient configuration of 50–60 cm. On the other hand, it is "disturbed" by geological features and very much by narrow technical installations and/or small amounts of modern metal waste.

Digital image processing

Digital image processing of geophysical data represented a milestone in the field of archaeological prospecting and a crucial step in making survey results intelligible to both geophysicists and archaeologists. The potential for digital image processing of geophysical data compared to the isoline display ("contour" lines joining areas with the same magnetic intensity values) was recognized and applied very early in the history of archaeological prospecting (Scollar and Krückeberg, 1966). Meanwhile, sophisticated programs are available that enable one to treat the data with a multitude of correcting and processing tools appropriate for the requirements of the different instruments used in archaeological prospection (Schmidt, 2002; David et al., 2008).

A survey area should be measured by a sampling interval of at least 25 × 50 cm or even better 25 × 25 cm. The magnetometer data (the relative intensity versus x-y-position) is then converted to a gray-shaded image, displayed on the computer screen, and then exported and stored as a tif file. The reason for the display as a gray-shaded image is twofold: (1) the intensity of the magnetic field is a single-parameter data set, so the only physically sensible display of such data is using a single-parameter scale and (2) the human eye is capable of discriminating up to 60 grayscales. Hence, the display of magnetometer data as a grayscale plot of 256 gray shades (from white to black) is a crucial tool for the success of this prospection method. The popular term for the resulting image of the magnetometer data is "magnetogram," although this term is also used in geomagnetism to describe the variation of the Earth's magnetic field with time.

Soil magnetism

Small-scale or local deviations in the intensity and/or direction of the Earth's normal magnetic field are caused simply by the magnetic contrast between buried archaeological features and the adjacent soils and sediments; these variations enable magnetometers to detect archaeological sites beneath the ground. The enhancement of ferrimagnetic minerals in the topsoil is a common property of almost all soils worldwide (Le Borgne, 1955; Mullins, 1977; Fassbinder and Stanjek, 1993). It has been observed even in very magnetic soils of volcanic origin (Tucker, 1952; Fassbinder et al., 2009).

Enrichment and separation of these heavy ferrimagnetic minerals to form magnetic patterns can occur mechanically by wind or water (Fassbinder et al., 2005) as well as by pedogenic processes in soils, but it is produced most commonly by the heating of soils during natural fires and, more intensively, by the use of fire concentrated in limited spaces by people. Once produced in the topsoil, these minerals end up in ditches, pits, palisades, or postholes, and they will generate a magnetic anomaly that can be sensed by instrumentation above the ground.

Formation of magnetic minerals in soils

Enrichment of ferrimagnetic minerals in topsoils was recognized and described by Le Borgne (1955, 1960) and initially ascribed to the widespread use of fire during forest clearance or other anthropogenic activities. But it soon became clear that many archaeological features previously detected by magnetometers as positive anomalies (the feature in question shows stronger magnetic signals than surrounding soils or the Earth's field in general) were never exposed to fire (Fassbinder, 1994). Tite and Linington (1975) showed that climate also has a huge influence on magnetic susceptibility due to the formation of magnetic minerals (magnetite and maghemite) in soils (magnetic susceptibility is the ratio of the magnetization M of a material to the magnetic field H inducing it). The distinction between magnetite and maghemite as well as other magnetic sources is of great importance (Tables 1 and 2). The presence of one of them may provide valuable information about the history of an archaeological site since it allows one to discriminate between modern metallic waste, burned features such as kilns and fireplaces, and pure organic waste pits, cesspits, or bogholes – e.g., in horse stables of Roman camps (Fassbinder 2010a).

Le Borgne (1955, 1960) ascribed the formation of maghemite either to:

Magnetometry for Archaeology, Table 1 Occurrence and origin of magnetic iron oxides and sulfides in soils and archaeological layers and objects

Phase	Origin		
	Pedogenic	Lithogenic	Anthropogenic
Magnetite	SP, SD	SD, PSD, MD	Industrial dust
Maghemite	From Gt, Lp by fire	Oxidized Mgt	Oxidized Mgt, industrial dust, ceramics
Greigite	SP, SD	??	No
Hematite	Yes	Yes	Fire, industrial dust, ceramics
Goethite	Yes	Yes	No
Ti-Mgt, Ti-Mgh	No	Yes	Ceramics

SP, super paramagnetic; PSD, pseudo-single domain; SD, single domain*; MD, multi-domain; Gt, goethite; Lp, lepidocrocite; Mgt, magnetite

*Single-domain grains are too small to accommodate a domain wall and hence exhibit only one magnetic direction. They must change their magnetization by rotation. They exhibit a unique thermoremanent magnetism (TRM, see below) blocking temperature, while the TRM of larger multi-domain grains is complicated by the mobility of the domain walls (Dunlop and Özdemir, 1997)

Magnetometry for Archaeology, Table 2 List of the specific magnetic susceptibility (nondimensional SI units) of natural magnetic minerals and ferrous iron

Remanence-carrying minerals	Specific susceptibility (SI units)
Ferrous iron	2×10^7
Magnetite (Fe_3O_4)	5×10^4
Maghemite ($\gamma - Fe_2O_3$)	4×10^4
Pyrrhotite (Fe_2S_8)	5×10^3
Ilmenite ($FeTiO_3$)	200
Lepidocrocite (FeOOH)	70
Goethite ($\alpha - FeOOH$)	70
Hematite (Fe_2O_3)	60

1. Fermentation, with reduction by the decomposition of organic materials in anaerobic soils, followed by reoxidation to maghemite during dry weather periods under aerobic conditions
2. Natural and anthropogenic fire:

$\propto - Fe_2O_3$ hematite	reduction	Fe_3O_4 magnetite	oxidation	$\gamma - Fe_2O_3$ maghemite

Both processes start with hematite, have magnetite as an intermediate phase, and should finally yield maghemite. Synthesis experiments and observations in nature, however, indicate that the processes forming maghemite are different and more complex. Four precursors are known for maghemite:

1. Magnetite inherited from a parent rock or sediment oxidizes (partially) to maghemite. These maghemites usually have grain sizes in the range of millimeters. This process has been observed, e.g., for titanomagnetites (Fitzpatrick and Le Roux, 1976).
2. Depending on the particle size, lepidocrocite (γ – FeOOH) dehydrates between 260 °C and 300 °C to maghemite (Scheffer et al., 1959; Schwertmann and Taylor, 1979).
3. In the presence of organic matter, goethite is transformed to maghemite during bushfires (Schwertmann and Fechter, 1984; Anand and Gilkes, 1987; Stanjek, 1987).
4. Siderite ($FeCO_3$) oxidizes readily to maghemite when it is gently heated (Van der Marel, 1951; Schwertmann and Heinemann, 1959).

Hematite, however, has not yet been observed acting as a precursor for maghemite or magnetite. Apart from the fact that hematite is not always present in soils in which maghemite is found, it has not been conclusively shown that hematite can be reduced to magnetite under natural soil conditions. Mineral assemblages (Anand and Gilkes, 1987; Stanjek, 1987) as well as calculations (Scotter, 1979) suggest that the maximum temperatures reached in topsoils during natural episodes of burning are about 300–400 °C, and at these temperatures, a reduction of hematite by reducing agents such as organic carbon is unlikely.

The formation of magnetite in soils and sediments is still debated with some controversy in the literature (cf. Oldfield, 1992; Dearing et al., 1997). Two pathways for its pedogenic formation have been proposed:

1. Inorganic: in synthesis experiments, the controlled oxidation of ferrous iron yields magnetite (David and Welch, 1956). This inorganic formation may also take place in soils (Maher and Taylor, 1988).
2. Biologically: the biologically controlled formation of magnetite (BCM) by soil bacteria has been observed by Fassbinder et al. (1990). The intracellular magnetite crystals formed in this way may be arranged in chains and have similar size and shape to magnetite that was extracted from soils. Furthermore, dissimilatory iron-reducing bacteria such as GS-15 (Lovley et al., 1987) may form magnetite extracellularly (referred to as biologically induced formation of magnetite or BIM) in soil.

The formation of greigite (Fe_3S_4) in soil can occur by two pathways:

1. Inorganic: it has been shown in synthesis experiments under controlled conditions that greigite can be produced by combining aluminum ferrous sulfate with sodium sulfide, autoclaving, and quenching (Uda, 1965).
2. Biologically controlled: evidence of magnetotactic greigite bacteria was found by Mann et al. (1990). Evidence of biologically unidentified soil bacteria was reported by Stanjek et al. (1994) and Fassbinder and Stanjek (1994). Both greigite and magnetite magnetotactic bacteria are reported to precipitate either magnetite or greigite. The crystals form within a membrane and are arranged into chains. They can be preserved as magnetofossils in archaeological layers, soils, and sediments and in the geological record (Petersen et al., 1986).

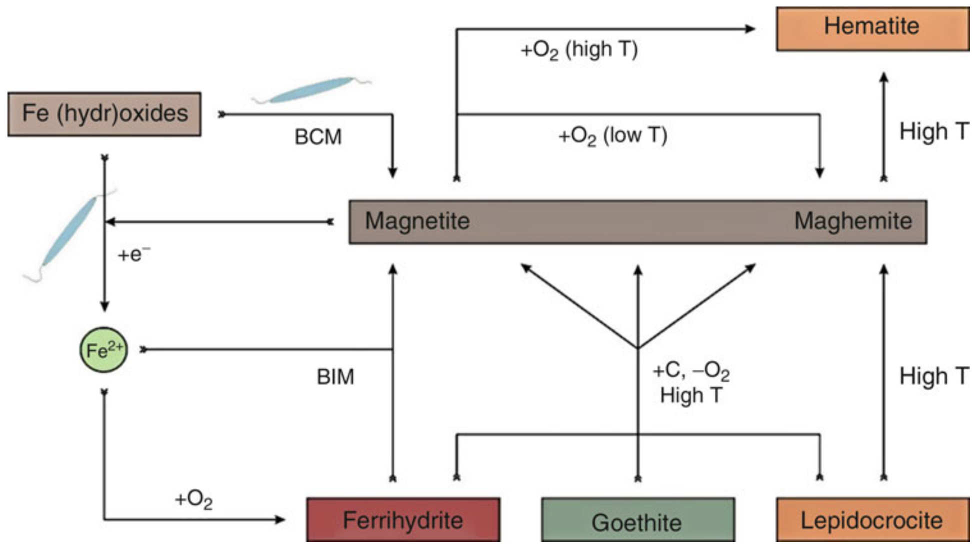
The formation and transformation process of iron oxides in soils is a complex interrelation between geochemistry, temperature, temporary weather conditions, and climate (Schwertmann, 1988). A simplified chart illustrating the different pathways in the formation and transformation processes for magnetite and maghemite that may occur in natural soils and sediments is shown in Figure 3.

Induced magnetization

If a ferromagnetic sample is exposed to a magnetic field, a magnetization J_i will be induced in the sample. Magnetometer measurements in an applied field (in the range of the Earth's magnetic field) provide information on the nature and quantity of the magnetic minerals and can therefore monitor changes that occur in a sample as a result of heating. Examples of archaeological sites where the resulting magnetic anomalies can be explained by the induced magnetization of the features come from archaeological sites in the Nile Delta (Becker and Fassbinder, 1999) and from a kiln site near Regensburg, Bavaria (Fassbinder et al., 2011) (see below, Figures 5 and 9). Knowledge of the origin and formation of iron oxides in soils and the specific magnetic susceptibility values of these minerals and of ferrous iron (Tables 1 and 2) allow improved specification and analysis, and thus a better and more detailed interpretation, of the intensity of a magnetic anomaly.

Along with induced magnetization due to the formation and enrichment of fine-grained magnetic particles, the remanent magnetization of archaeological features and objects also plays a significant role in generating magnetic anomalies (see below).

The exact connection between an anomaly and the buried archaeological structure (body) is not always clear – usually because the material causing the anomaly is not knowable without an archaeological excavation. The interpretation of an anomaly depends on whether the magnetization is induced by the present Earth's magnetic field only (and is therefore parallel to the present field direction) or is mainly remanent (permanent) and aligned with an ancient field, for example, the ancient magnetization may deviate at some angle from that of the present field direction if the buried structure was magnetized in situ by a burning or heating event (i.e., TRM or thermoremanent magnetization). The Koenigsberger ratio (Qn) of remanent to induced magnetization is therefore an



Magnetometry for Archaeology, Figure 3 Flowchart showing the possible formation pathways of maghemite and magnetite in soils (After Stanjek, 1999, pers. communication; and Schwertmann, 1988). Transformations depend on high or low temperatures (T), presence or absence of carbon and oxygen, and magnetotactic bacteria (BCM, biologically controlled formation of magnetite; BIM, biologically induced formation of magnetite).

important parameter that may help with the archaeological interpretation of the results. While the remanent versus induced magnetization for archaeological soils is in the range of Qn $\sim$ 1, in burned bricks and heated soils, it can reach values of >10 (depending very much on the grain size of the magnetic minerals); in places struck by lightning, Qn can reach values of up to 500–700 (see below Figure 8).

The remanent magnetization in archaeological structures

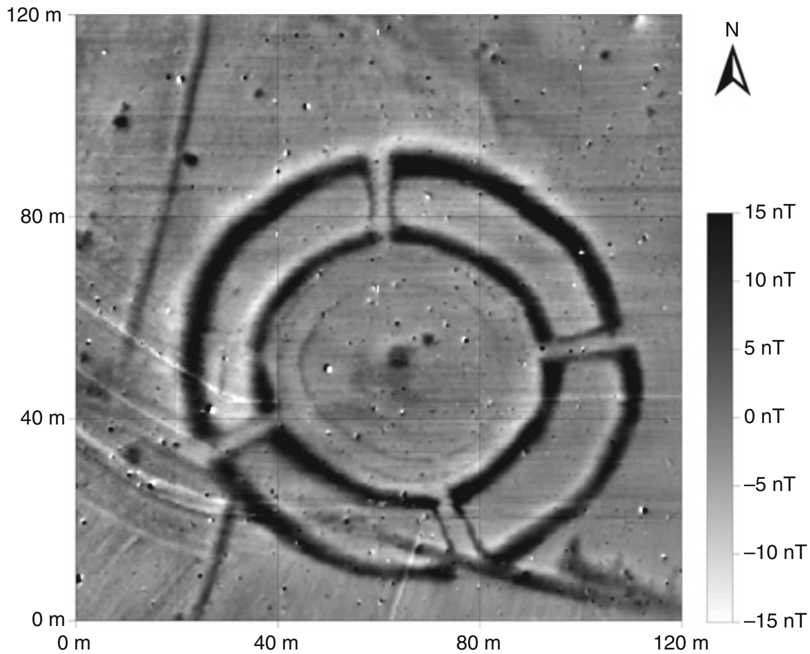
Nearly every rock, sediment, and fossil or archaeological soil has a remanent magnetization (Fassbinder, 1994; Dunlop and Özdemir, 1997). A primary natural remanent magnetization (NRM) can be acquired by four basic processes: thermoremanent, detrital remanent, chemical remanent, and lightning-induced remanent magnetization.

Thermoremanent Magnetization (TRM)

If rocks, sediments, or soils are exposed to high temperatures, they become initially magnetized by a thermoremanent magnetization (TRM). When the constituent magnetic minerals cool through their curie (or blocking temperature) in the ambient geomagnetic field, the direction of their magnetization will be "blocked," aligned along the Earth's magnetic field direction at that time. Additional ferrimagnetic minerals such as maghemite will be created by the transformation of antiferromagnetic minerals such as goethite and lepidocrocite (see Figure 3). The high magnetic intensities caused by archaeological pottery kilns, fireplaces, and metal production sites originate from TRM, and they can be easily identified in the magnetogram (see also Figure 9 below). The thermoremanent magnetization occurs at the moment of last cooling, so the magnetic field recorded will be the one in existence at the most recent time of heating, which may be significantly different from the field of today.

Detrital Remanent Magnetization (DRM)

As an archaeological soil containing permanently magnetized oxide grains is deposited in water (e.g., in a pit, in a ditch, or in ground depressions), the grains tend to orient themselves in a position of minimum energy, i.e., with their magnetic axis aligned along or parallel to the ambient magnetic field direction. Although there is usually still some disorientation among many grains, a statistical alignment along the field direction in existence at the time remains; this is called DRM. If there are some grains that are sufficiently small relative to interstitial volumes, they will continue to align with the ambient field as they are buoyed somewhat by pore water trapped within the interstices of the soils. Such tiny grains can swing into alignment without being impinged by the surrounding sediments even after deposition. This is referred to as a postdepositional remanent magnetization (PDRM). Although such remanences are quite weak, they can result in a detectable magnetic anomaly if they remain in situ. Mixing of these sediments through various disturbances such as excavation and backfilling of the material into a ditch or pit so that magnetic minerals and their domains are randomized results in a "mechanical demagnetization" (Fassbinder and Becker, 2003; Fassbinder and Gorka, 2009b; Fassbinder, 2010b).



Magnetometry for Archaeology, Figure 4 Steinbrunn, Austria. Magnetogram of the Neolithic ring ditch enclosure. The ditch is filled by topsoil, but the palisades and a pit in the center of the enclosure also show up as a normal positive (*black*) anomaly. Magnetometer survey, CS-2 Scintrex magnetometer, sensitivity ±1 picotesla, in variometer (duo-sensor) configuration, 40 × 40 m grid, spatial resolution 12.5 × 50 cm, interpolated to 25 × 25 cm, total Earth's magnetic field at the site 48,090 ± 20 nT, date May 1997, angle of dip +65°, *gray-shaded* plot in 256 grayscales from positive (*black*) to negative (*white*).

Chemical Remanent Magnetization (CRM)

At normal Earth-surface temperatures and for sufficiently small magnetic particles, thermal fluctuations dominate and the alignment of particles is randomized. But if the particle volume grows through a critical value, magnetostatic forces overcome the thermal fluctuations and produce a chemical or crystallization remanent magnetization.

Lightning-Induced Remanence (LIRM)

A lightning strike can produce a magnetization in the area immediately surrounding the impacted location, including rocks, sediments, and soils. Such a lightning strike magnetization is easy to recognize by its anomalously high Koenigsberger ratio (Qn), its magnetic intensity (>200 nanoteslas), but with respect to magnetic prospecting also by its typical star-shaped structures (see below Figure 8) (Maki, 2005; Fassbinder and Gorka, 2009a).

The interpretation of the magnetometer data and of the magnetogram image

In a simple form, the magnetogram offers a readily recognizable distribution of the structures beneath the soil. Knowledge of soil magnetic properties combined with the descriptive and comparative methods of archaeological interpretation forms the basis for obtaining optimal results using this approach (Neubauer and Eder-Hinterleitner, 1997; Fassbinder and Irlinger, 1999).

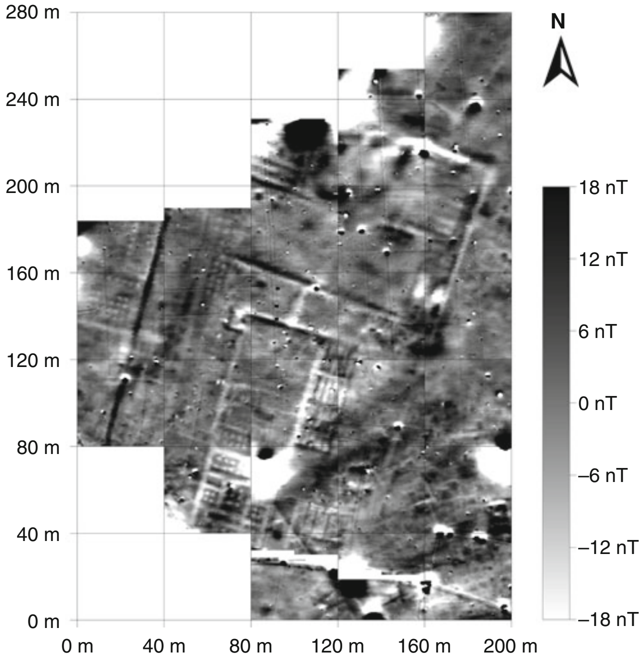
Positive magnetic anomalies on archaeological sites

The most common situation on nearly all soils of the world is an enhanced magnetization and magnetically enriched topsoil. Hence, any pit, ditch, or wooden posthole refilled by topsoil will generate a positive magnetic anomaly. If such a structure is refilled by homogeneous topsoil, the intensity and the shape of the anomaly is proportional to the size and volume of the archaeological feature. Any concentration of pottery, ash or burned material, and solid rocks or other materials will cause a deviation and thus will determine the intensity and the shape of the magnetic anomaly. The Neolithic ring ditch from Steinbrunn (northeastern Austria) gives an ideal example of this situation (Figure 4).

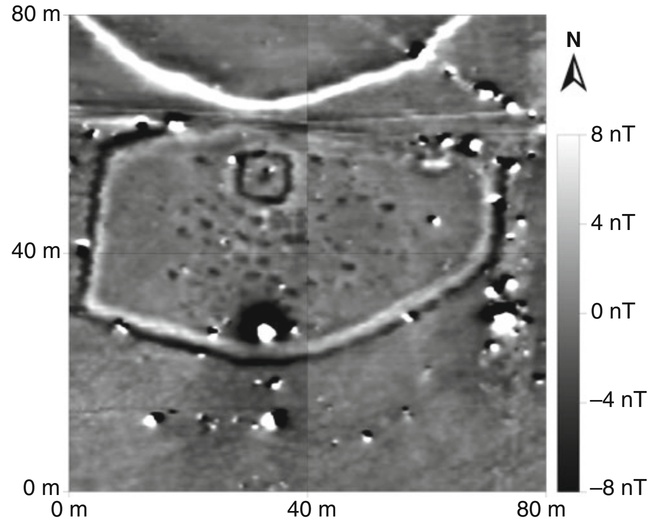
Negative magnetic anomalies on archaeological sites

Negative Magnetic Anomalies May Have Numerous Causes

1. The material of the archaeological structure possesses a lower magnetic susceptibility than the adjacent topsoil. For example, this will be the case if there are foundations of weakly magnetic limestone or sandstone in the ambient magnetic soil but also when mud bricks



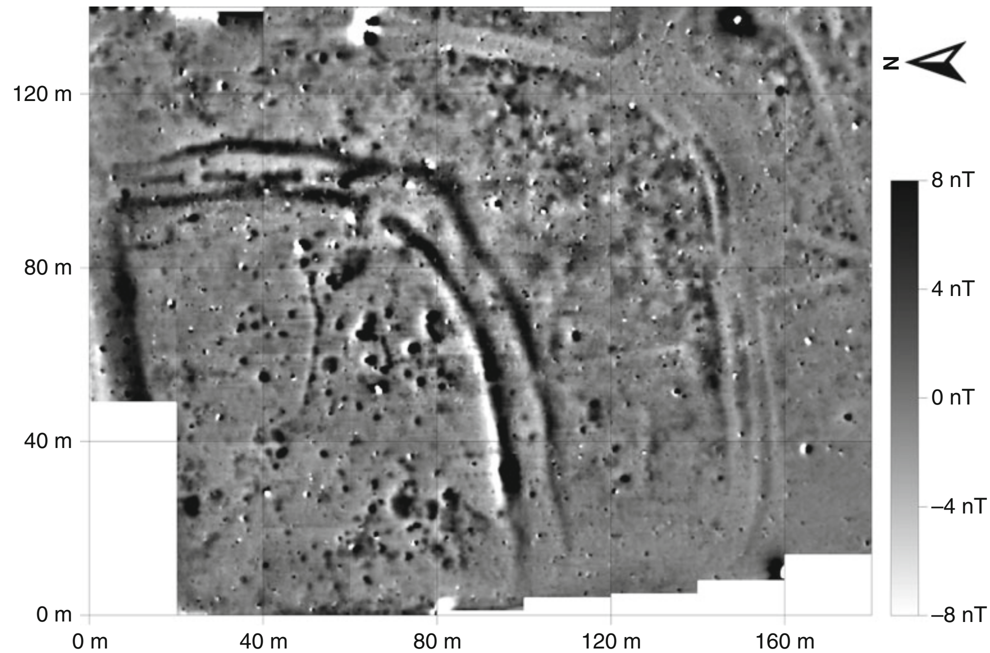
Magnetometry for Archaeology, Figure 5 Qantir, Egypt. A palace of Ramses II. The mudbrick walls are made using materials of different magnetic susceptibilities. This explains why they show up in some areas as a positive (black) anomaly but in other areas as a negative (*white*) anomaly. However, the bases of stone columns were made of sand and limestone, so they always show a negative (*white*) anomaly. Magnetometer survey with SmartMag SM4G special cesium magnetometer, sensitivity ±10 picotesla, variometer (duo-sensor) configuration, 40 × 40 m grid, spatial resolution 12.5 × 50 cm, interpolated to 25 × 25 cm, intensity of total Earth's magnetic field at the site 43,280 ± 20 nT, date October 1998, angle of dip +45°, *gray-shaded* plot in 256 grayscales from positive (*black*) to negative (*white*).



Magnetometry for Archaeology, Figure 6 Bajkara, Kazakhstan. Magnetogram of the Islamic cemetery adjacent to a Scythian kurgan. Magnetometer survey with SmartMag SM4G special cesium magnetometer, sensitivity ±10 picotesla, variometer (duo-sensor) configuration, 40 × 40 m grid, spatial resolution 12.5 × 50 cm, interpolated to 25 × 25 cm, intensity of total Earth's magnetic field at the site 56,230 ± 30 nT, date June 1999, angle of dip +70°. Note that the gray-shaded image was *inverted* and shows negative anomalies in black; the single graves, inside the oval, show up as negative (*black*) anomalies.

are made from more sandy material than the surrounding mud or the debris of ceramic, pottery, and burned materials. The ground plan of a palace of Ramses II in Egypt shows up as a negative magnetic anomaly for extensive parts of the wall, but in some areas, it also appears as a positive one depending on the magnetic susceptibility of the mud bricks (Figure 5). The bases of the columns, however, were always visible as a negative anomaly because of their limestone and/or sandstone foundations. In situ measurements of the magnetic susceptibility of mud bricks confirmed this hypothesis (Fassbinder, 2015b).

2. A negative magnetic anomaly may also occur whenever there was an excavated pit that was immediately refilled by the same material. The resulting magnetic field intensity, which is due to the induced plus the remanent magnetization, is diminished by the remanent part of the soil; in other words, whatever remanence the soil previously had is now randomized by the reburial process and hence nullified. Hence, the resulting magnetogram will show a negative anomaly compared to the adjacent intensity within intact soil areas. Similar case histories of magnetic anomalies, which could most likely be explained this way, are reported, albeit rarely (Fassbinder and Irlinger, 1998b; Fassbinder, 2010b). A comprehensive example of such a case was found in the steppes of northeastern Kazakhstan (Figure 6). Adjacent to a Scythian kurgan, there was an Islamic cemetery of the seventeenth century. The site consists of an oval ditch that is still 40 cm deep and visible at the ground surface. Inside the oval, there is a small memorial square place also enclosed by a small ditch. In the remaining area, although there is nothing else visible in the topography, roughly 40 negative (white) anomalies were detected, ca. 1 × 2 m in size; these can very probably be ascribed to the pits of a burial yard. These pits were excavated to a depth of ca. 1.8–2 m for the funeral interments and then immediately refilled with the same loess sediment that was removed to create the grave pits (Fassbinder and Becker, 2003).
3. A geochemical process such as the partial dissolution of ferrimagnetic particles and the precipitation of iron oxides as goethite, ferrihydrite, and lepidocrocite is another basic cause for the occurrence of a negative magnetic anomaly. In soils where there is stagnant moisture in combination with a changing groundwater table, an originally positive anomaly can be



Magnetometry for Archaeology, Figure 7 Riekofen, Bavaria. The Neolithic site is enclosed by four concentric ditches; the two inner circles show up as a positive trace (*black*) and the two outer ditches as negative (*white*). Magnetometer survey with CS-2 Scintrex magnetometer in variometer (duo-sensor) configuration, sensitivity ± 1 picotesla, 40×40 m grid, spatial resolution 12.5×50 cm, interpolated to 25×25 cm, intensity of total Earth's magnetic field at the site $47{,}920 \pm 20$ nT, date April 1997, angle of dip $+65°$, *gray-shaded plot* in 256 grayscales from positive (*black*) to negative (*white*).

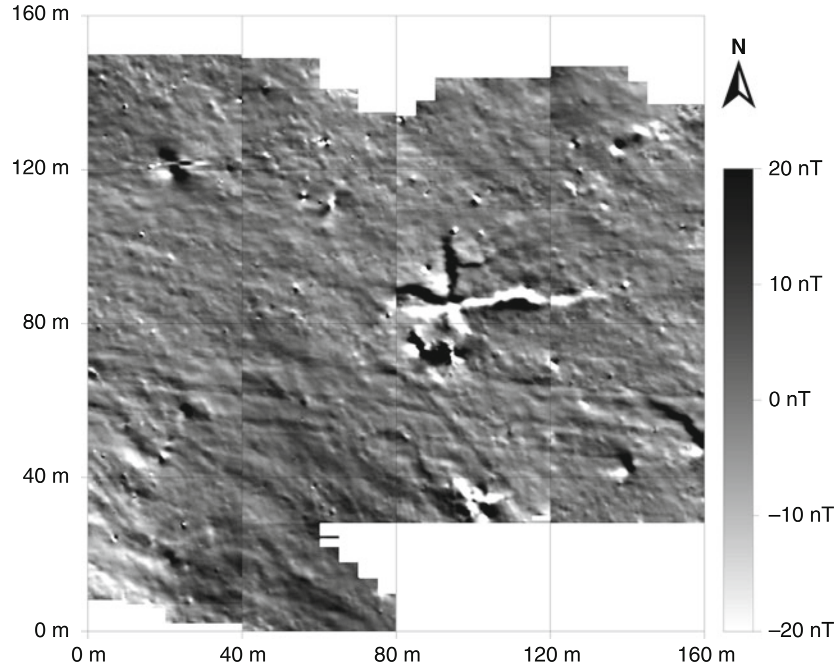
transformed into a negative one. A former ditch of an earthwork that was originally filled with topsoil and organic material of high magnetic susceptibility can eventually show up as a negative anomaly. A good example for this is the Neolithic earthwork of Riekofen in Bavaria. The central settlement lies on a slight hill only 1.5 m above a small river. The inner ditch shows a normal positive magnetization, whereas the outer one was partly flooded by water and shows a "negative" trace (Figure 7) (Fassbinder and Irlinger, 1998a; Schleifer et al., 2003). Temporary soil wetness is also one of the main reasons why the large ditches of Celtic square enclosures become magnetically "invisible" despite the fact that they were clearly detected by air photos and aerial prospecting (Fassbinder, 2005; Berghausen, 2015).

Lightning-induced remanence-based features

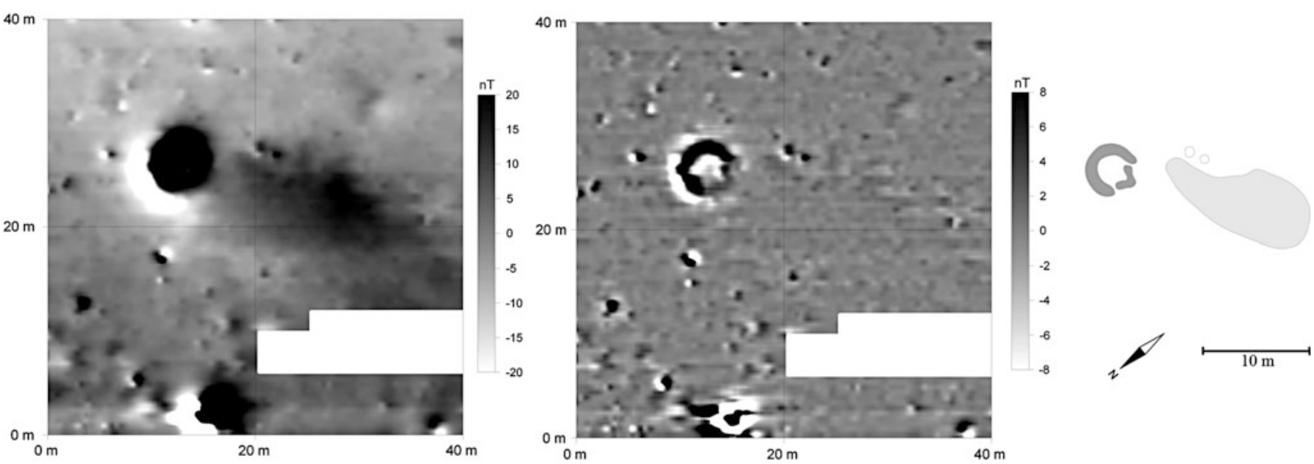
A wide range of examples can be offered of lightning-induced magnetic anomalies in archaeological sites. In early surveys, such anomalies were often misunderstood and erroneously interpreted. Lightning-induced anomalies are typically star shaped and characterized by the varying directions of their remanence. While thermoremanent magnetization of archaeological features reveals anomalies that are more or less parallel to the Earth's magnetic field at the time of heating, lightning-induced remanence has erratic directions, which follow the traces of the electric current in the soil. The highest density of lightning-induced anomalies was found associated with the famous geoglyphs of Nazca, Peru (Figure 8). Although they are located in one of the driest areas on Earth (average precipitation of less than 5 mm per year), these sites are situated on the borderline between the desert and fertile land, and they were exposed extensively to lightning strikes in the past (Eitel pers. comm.; Eitel et al., 2005). On a measured area of ca. 100 ha (five trapezoidal geoglyphs around Palpa, Peru), evidence for a total of 50 lightning strikes was found (Fassbinder and Gorka, 2009a).

Thermoremanent magnetic anomaly

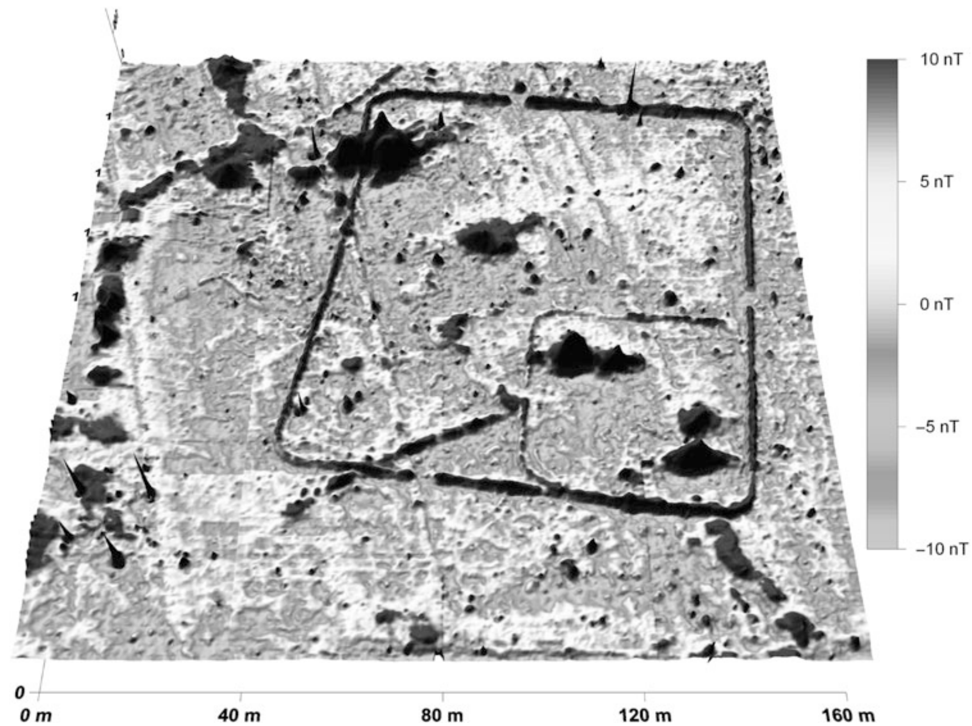
The example of a kiln, which was discovered by magnetic prospecting near the Roman fort of Großprüfening (city of Regensburg), is shown in Figure 9. The normalized magnetic anomaly of the total field measurement possesses a large positive (black) round shape (ca. ± 20 nT) with an oval-shaped area adjacent to it; these indications were due to an enrichment of fine-grained magnetic minerals in the topsoil (± 8 nT). Applying a high-pass filter to the data set enables us to visualize the round shape and the ground plan of the furnace in all its details, including the opening of the kiln. The magnetic traces of the ash deposits, located beyond the opening, were removed by the high-pass filter (Fassbinder et al., 2011).



Magnetometry for Archaeology, Figure 8 Reloj Solar, Peru. A typical star-shaped magnetic anomaly of a lightning strike on a trapezoidal geoglyph. Magnetometer survey with SmartMag SM4G special cesium magnetometer, sensitivity ± 10 picotesla, variometer (duo-sensor) configuration, 40×40 m grid, spatial resolution 12.5×50 cm, interpolated to 25×25 cm, intensity of total Earth's magnetic field at the site $25{,}350 \pm 20$ nT, date August 2005, angle of dip $= -5°$, gray-shaded plot in 256 grayscales from positive (*black*) to negative (*white*).



Magnetometry for Archaeology, Figure 9 Großprüfening (Bavaria). Typical magnetic anomaly of a huge pottery kiln, with traces of ash layers that are visible only in the total field mode (*left image*). Magnetometer survey with SmartMag SM4G special cesium magnetometer, sensitivity ± 10 picotesla, variometer (duo-sensor) configuration, 40×40 m grid, spatial resolution 12.5×50 cm, interpolated to 25×25 cm, intensity of total Earth's magnetic field at the site $48{,}330 \pm 20$ nT, date November 2010, angle of dip $= +65°$, *gray-shaded* plot in 256 grayscales from positive (*black*) to negative (*white*). Images from *left* to *right*: total field measurement; after application of a high-pass filter; archaeological interpretation.



Magnetometry for Archaeology, Figure 10 Burgsalach, Bavaria. The magnetometer image processed as a pseudo-3D image of a Roman camp revealed very clearly two archaeological phases of the fortification. Magnetometer survey with SmartMag SM4G special cesium magnetometer, sensitivity ± 10 picotesla, variometer (duo-sensor) configuration, 40×40 m grid, spatial resolution 12.5×50 cm, interpolated to 25×25 cm, intensity of total Earth's magnetic field at the site 48,220 $\pm$ 20 nT, date April 2008, angle of dip $= 65°$, *gray-shaded* plot in 256 grayscales from positive (*black*) to negative (*white*).

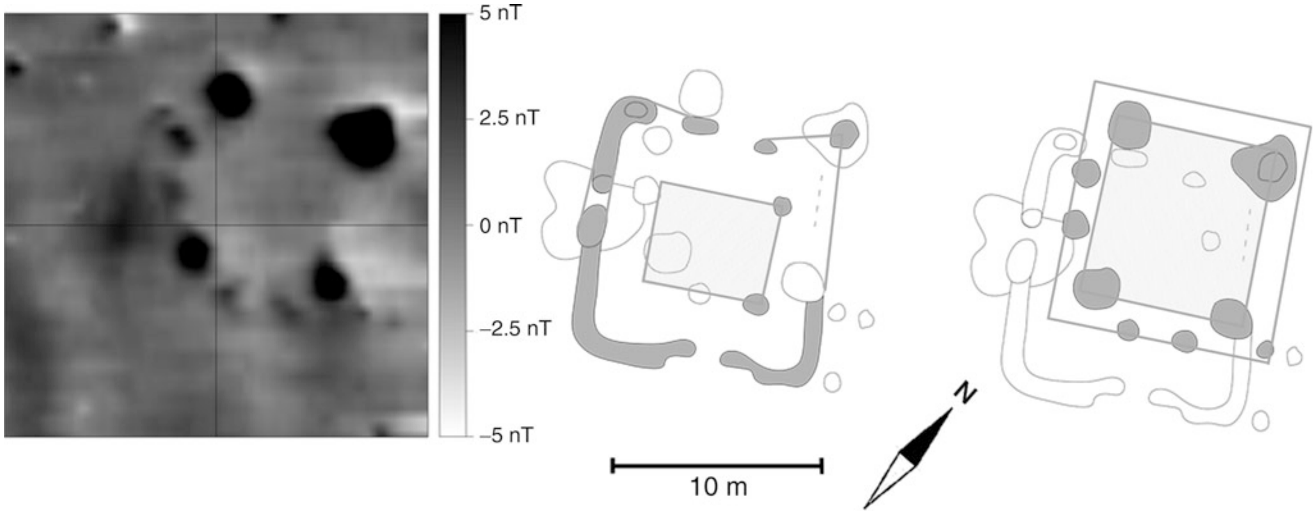
Magnetic prospection of archaeological stratigraphy

Magnetic prospecting is not very suitable for detecting archaeological layers and discriminating them from each other. Nevertheless, there are some case studies that demonstrate the possibility of distinguishing at least two phases of a stratigraphic archaeological sequence (Fassbinder and Irlinger, 1999). The Roman camp of Burgsalach (Figure 10) provides one such example. The small Roman camp, ca. 40×40 m in size, was fortified by a palisade (visible as a small, narrow ditch), and then in a second phase, it was overbuilt and enlarged to a camp of ca. 100×120 m. The older trace of the palisade was enclosed by the new one, and it became visible to the magnetometer at the junction of both constructions. This geophysical interpretation is supported by archaeological interpretations based on the ground plan of the site. The symmetry and the entrances of the later camp are based on the remains of the smaller and older camp (Fassbinder and Gorka, 2009b).

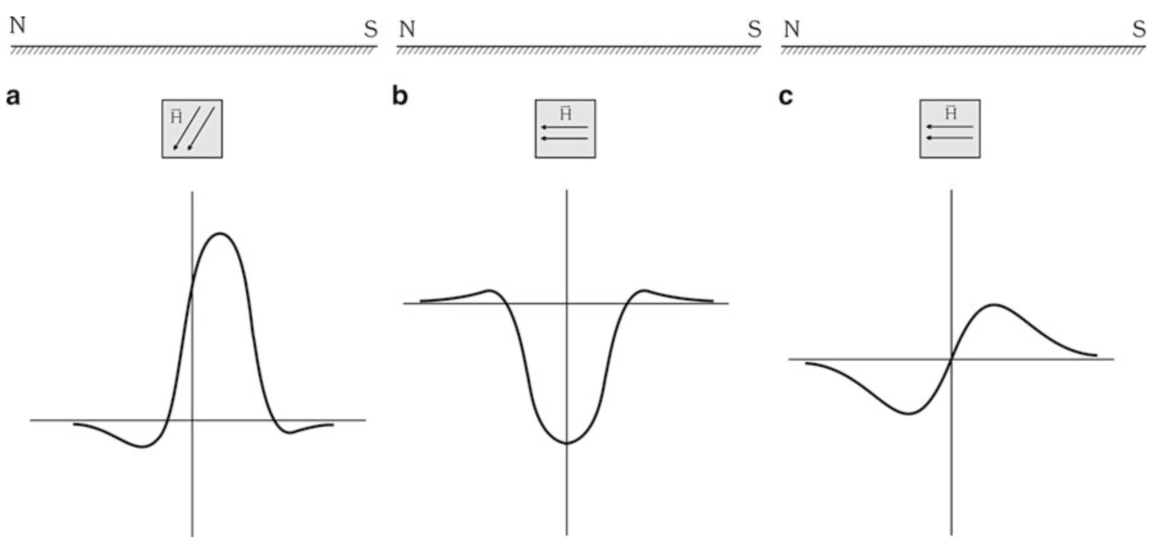
Celtic square enclosures are typical earthwork constructions abundant in southern Bavaria, in Baden-Württemberg, as well as in France. Magnetic prospecting of nearly 40 sites in Bavaria has revealed the main characteristics of these monuments (Fassbinder, 2005). Almost all consisted of an earth wall that was enclosed by a ditch, which was partly filled by water. Some of these ditches contained stagnant water, and thus they could hardly be recognized in the resulting magnetogram. Despite their large size (from 1 to 5 ha), only a few buildings could be found inside. Many of these buildings were destroyed by fire, and the resulting magnetogram of these buildings shows a high intensity. With the help of "archaeological knowledge" and the excavation report of a similar type of building with two phases (Möslein, 2002), it was possible to interpret the magnetogram (Figure 11).

Magnetic prospection near the geomagnetic equator

Although there are numerous case studies of magnetic prospection for archaeological sites in the northern hemisphere, only rare papers report on sites located near the geomagnetic equator (Tite, 1966; Fassbinder and Becker, 1999; Magnavita and Schleifer, 2004; Schmidt et al., 2009; Fassbinder and Gorka, 2011). There are probably two reasons for this. First, geophysics is well established as a prospecting method for archaeological fieldwork in Europe, Russia, and North America, as well as in China and Japan, but it is poorly established in the countries at the equatorial latitudes. Second, the results of magnetometer surveys near the geomagnetic equator are complex



Magnetometry for Archaeology, Figure 11 Itzling, Bavaria. The ground plan of a typical pile dwelling that was found inside a square enclosure revealed two archaeological phases. By comparing the magnetometer data with archaeological excavations from other sites, it was possible to infer two archaeological phases. Magnetometer survey with SmartMag SM4G special cesium magnetometer, sensitivity $\pm$10 picotesla, variometer (duo-sensor) configuration, 40 $\times$ 40 m grid, spatial resolution 12.5 $\times$ 50 cm, interpolated to 25 $\times$ 25 cm, intensity of total Earth's magnetic field at the site 48,180 $\pm$ 20 nT, date September 2011, angle of dip = +65°, gray-shaded plot in 256 grayscales from positive (*black*) to negative (*white*).



Magnetometry for Archaeology, Figure 12 Idealized shape of the magnetic anomaly of a cubic body measured by a total field magnetometer (**a**) at a latitude of 50° north, angle of dip ca. 70°; (**b**) at the geomagnetic equator, angle of dip = 0°; (**c**) measured with a fluxgate system (vertical sensor) at the geomagnetic equator.

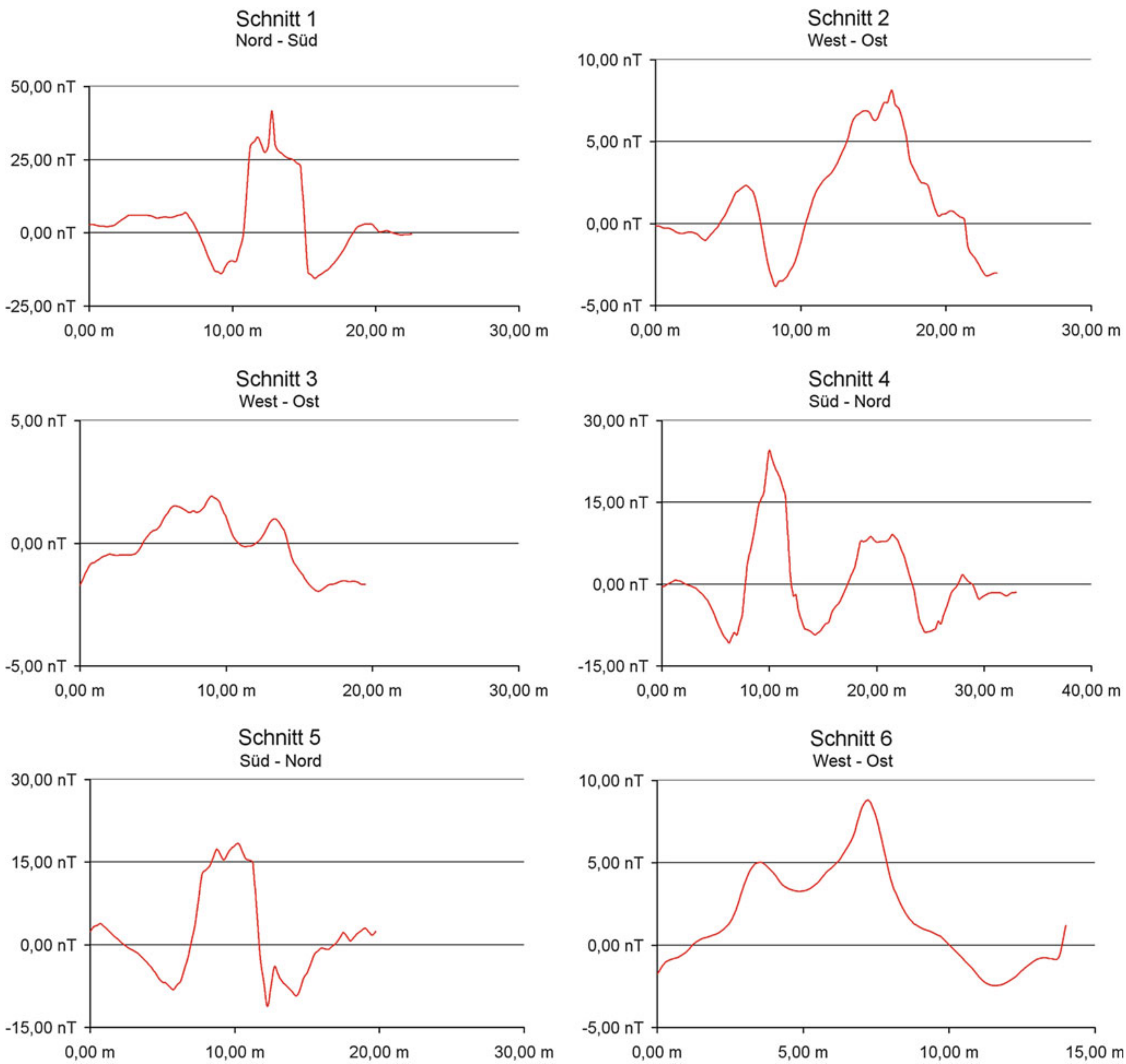
and require special knowledge for proper archaeological interpretation. The shape of the magnetic anomaly of the same feature varies dramatically depending upon latitude as well as the type of magnetometer used (see Figure 12).

A case study undertaken in Bolivia demonstrates the difficulties. The pre-Hispanic archaeological sites and ring ditches near Bella Vista in the lowlands of the Llanos de Moxos (northern Bolivia) were discovered after a large forest clearing in 1999. Initial excavations by archaeologists of the German Archaeological Institute revealed the occurrence of single burials inside the ditches, but no further structures or traces of settlements were discovered. The magnetogram (Figure 13) reveals clearly all the problems involved in the interpretation of magnetograms near the geomagnetic equator. Although there is a full ring, this ditch is clearly visible only in the northern and southern parts. This result compares quite well with the theoretical prediction and the shape of magnetic anomalies at the Equator (see Figure 12).

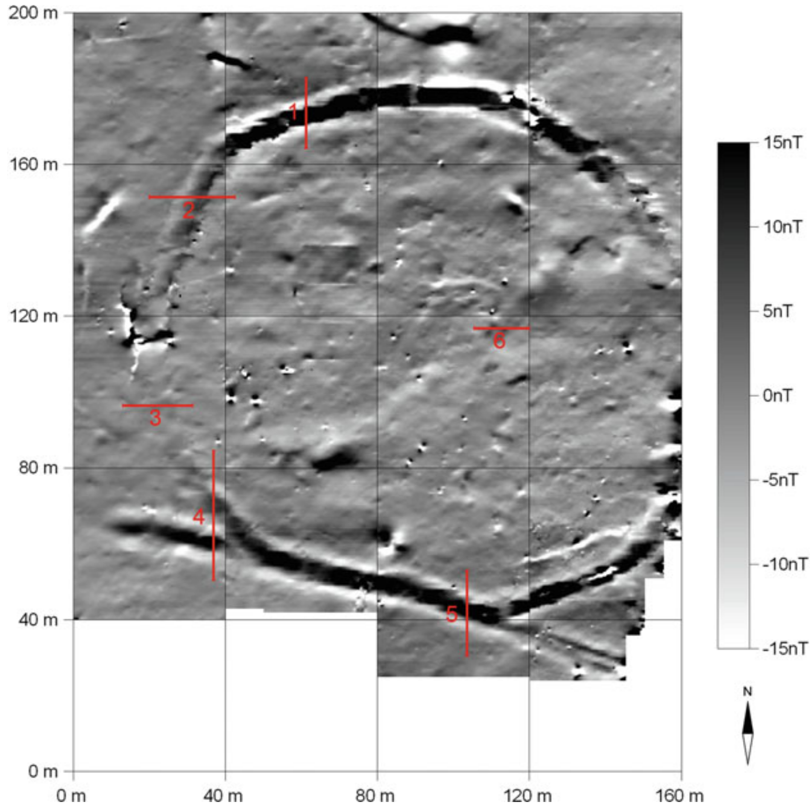
Summary

Without magnetic prospecting, many details of an archaeological site would probably remain overlooked and unexplored in the subsequent excavation phase. However, magnetic prospection can be successful only on sites where there is a magnetic contrast between the archaeological structures and the adjacent undisturbed soil layers. Until today, no simple correlation between the variety of different geochemical conditions and soil magnetic properties has been identified. At the present time, there is no way to forecast soil magnetic properties and hence whether magnetic prospecting will be successful or not.

Magnetic prospecting can provide detailed maps of ancient settlements and even entire ancient cities, as well as monumental buildings from different time periods. In particular, the prospecting of a multiplicity of sites from



Magnetometry for Archaeology, Figure 13 (Continued)



Magnetometry for Archaeology, Figure 13 Bella Vista (Bolivia). *Left*: selected profiles across archaeological structures. *Right*: magnetogram of a typical ring ditch of pre-Hispanic cultures. The northern and southern parts of the ring ditch are clearly visible, while the eastern and western parts of the ring are nearly faded out. Magnetometer survey with SmartMag SM4G special cesium magnetometer, sensitivity ±10 picotesla, variometer (duo-sensor) configuration, 40×40 m grid, spatial resolution 12.5×50 cm, interpolated to 25×25 cm, intensity of total Earth's magnetic field at the site $24{,}000 \pm 20$ nT, date August 2010, angle of dip $= -5°$, *gray-shaded* plot in 256 grayscales from positive (*black*) to negative (*white*).

the same category and/or archaeological period yields valuable information for archaeological and geophysical research as well as for cultural heritage protection (Fassbinder, 2005, 2010a; Berghausen, 2015). With an understanding of mineral and rock magnetic science and knowledge of their formation processes, the specific magnetic susceptibility of minerals (Tables 1 and 2), and the different types of remanent magnetization, it becomes possible to explain a significant number of details about buried archaeological features. The contribution of geophysics depends upon the magnetic anomaly, which is determined by the intensity and direction of the magnetization. Further analysis can discriminate between induced and remanent magnetization, and it may also yield information on different archaeological phases. The contribution of archaeology allows the possibility of roughly dating buried features by comparing the layout of structures to other findings already known from other excavations.

The methodology, instrumental measurement, sensitivity, and image processing for magnetic prospection will continue to improve, but already the results of magnetometer surveys are comparable to the maps of an archaeological excavation. Specific structures and the shape of the features allow a rough dating of a site, without any destructive removal of soil to expose the remains. Magnetometer surveys will never substitute for or replace an archaeological excavation, but they should precede every archaeological field project, in order to maximize the efficiency and minimize the physical destruction of an archaeological heritage.

Bibliography

Aitken, M. J., 1958. Magnetic prospecting I. *Archaeometry*, **1**(1), 16–20.

Aitken, M. J., 1974. *Physics and Archaeology*, 2nd edn. Oxford: Clarendon.

Anand, R. R., and Gilkes, R. J., 1987. The association of maghemite and corundum in Darling Range laterites, Western Australia. *Australian Journal of Soil Research*, **25**(3), 303–311.

Aspinall, A., Gaffney, C. F., and Schmidt, A., 2008. *Magnetometry for Archaeologists*. Lanham, MD: Altamira Press.

Becker, H., 1995. From nanotesla to picotesla – a new window for magnetic prospecting in archaeology. *Archaeological Prospection*, **2**(4), 217–228.
Becker, H., 1997. Hochauflösende Magnetik am Beispiel der archäologischen Prospektion. In Beblo, M. (ed.), *Umweltgeophysik*. Berlin: Ernst und Sohn, pp. 59–70.
Becker, H., and Fassbinder, J. W. E., 1999. In search for Piramesses – the lost capital of Ramesses II in the Nile delta (Egypt) by caesium magnetometry. In Fassbinder, J. W. E., and Irlinger, W. (eds.), *Archaeological Prospection: Third International Conference on Archaeological Prospection; Munich 9.–11. September 1999*. München: Bayerisches Landesamt für Denkmalpflege. Arbeitshefte des Bayerischen Landesamtes für Denkmalpflege 108, pp. 146–150.
Belshé, J. C., 1957. Recent magnetic investigations at Cambridge University. *Advances in Physics*, **6**(22), 192–193.
Benech, C., 2005. Étude des plans d'urbanisme antiques. *Dossiers d'Archéologie*, **308**, 12–19.
Berghausen, K., 2015. *Magnetometrische Untersuchungen an keltischen Viereckschanzen in Bayern*. München: Bayerisches Landesamt für Denkmalpflege and Volk Verlag. Schriftenreihe des Bayerischen Landesamtes für Denkmalpflege 9.
Chwala, A., Stolz, R., IJsselsteijn, R., Schulze, V., Ukhansky, N., Meyer, H.-G., and Schüler, T., 2001. SQUID gradiometers for archaeometry. *Superconductor Science and Technology*, **14**(12), 1111–1114.
Clark, A., 1996. *Seeing Beneath the Soil: Prospecting Methods in Archaeology*. London: Batsford.
David, I., and Welch, A. J. E., 1956. The oxidation of magnetite and related spinels. *Transactions of the Faraday Society*, **52**, 1642–1650.
David, A., Linford, N., Linford, P., Martin, L., and Payne, A., 2008. *Geophysical Survey in Archaeological Field Evaluation*, 2nd edn. Swindon: English Heritage.
Dearing, J. A., Bird, P. M., Dann, R. J. L., and Benjamin, S. F., 1997. Secondary ferrimagnetic minerals in Welch soils: a comparison of mineral magnetic detection methods and implications for mineral formation. *Geophysical Journal International*, **130**(3), 727–736.
Dunlop, D. J., and Özdemir, Ö., 1997. *Rock Magnetism: Fundamentals and Frontiers*. Cambridge: Cambridge University Press.
Eitel, B., Hecht, S., Mächtle, B., Schukraft, G., Kadereit, A., Wagner, G. A., Kromer, B., Unkel, I., and Reindel, M., 2005. Geoarchaeological evidence from desert loess in the Nasca-Palpa region, southern Peru: Palaeoenvironmental changes and their impact on pre-Columbian cultures. *Archaeometry*, **47**(1), 137–158.
Fassbinder, J. W. E., 1994. *Die magnetischen Eigenschaften und die Genese ferrimagnetischer Minerale in Böden im Hinblick auf die magnetische Prospektion archäologischer Bodendenkmäler*. Marie Leidorf: Buch am Erlbach.
Fassbinder, J. W. E., 2005. Methodische Untersuchungen zur Magnetometerprospektion von Viereckschanzen. In Neumann-Eisele, P. (ed.), *Viereckschanzen: Rätselhafte Bauwerke der Kelten*. Kelheim: Archäologisches Museum. Museumsheft 8, pp. 11–22.
Fassbinder, J. W. E., 2007. Unter Acker und Wadi: magnetometerprospektion in der Archäologie. In Wagner, G. A. (ed.), *Einführung in die Archäometrie*. Erlin: Springer, pp. 53–73.
Fassbinder, J. W. E., 2010a. Von Eining bis Ruffenhofen: Auf dem Weg zu einem Magnetogramm-Atlas der raetischen Limeskastelle – Ergebnisse der geophysikalischen Prospektion in Bayern. In P. (ed.), *Perspektiven der Limesforschung. 5. Kolloquium der Deutschen Limeskommission*. Beiträge zum Welterbe Limes 5. Stuttgart: Theiss, pp. 88–103.
Fassbinder, J. W. E., 2010b. Magnetometerprospektion des neolithischen Erdwerkes von Altheim. *Das archäologische Jahr in Bayern*, **2009**, 26–29.
Fassbinder, J. W. E., 2015a. Seeing beneath the farmland, steppe and desert soil: magnetic prospecting and soil magnetism. *Journal of Archaeological Science*, **56**, 85–95.
Fassbinder, J. W. E., 2015b. Magnetische Eigenschaften der archäologischen Schichten von Qantir (Ägypten). *Forschungen in der Ramses-Stadt*, **9**, 327–350.
Fassbinder, J. W. E., and Becker, H., 1999. Magnetic prospection of a megalithic necropolis at Ibbankatuvwa (Sri Lanka). In Fassbinder, J. W. E. (ed.), *Archaeological Prospection: Third International Conference on Archaeological Prospection; Munich 9.–11. September 1999*. München: Bayerisches Landesamt für Denkmalpflege. Arbeitshefte des Bayerischen Landesamtes für Denkmalpflege 108, pp. 106–109.
Fassbinder, J. W. E., and Becker, H., 2003. Magnetometerprospektion des großen Kurgans 1 von Bajkara. In Parzinger, H., Zajbert, V., Nagler, A., and Plesakov, A. (eds.), *Der grosse Kurgan von Bajkara: Studien zu einem skythischen Heiligtum*. Von Zabern: Mainz. Archäologie in Eurasien, Vol. 16, pp. 131–136.
Fassbinder, J. W. E., and Gorka, T. H., 2009a. Beneath the desert soil – archaeological prospecting with a caesium magnetometer. In Reindel, M., and Wagner, G. A. (eds.), *New Technologies for Archaeology: Multidisciplinary Investigations in Palpa and Nasca, Peru*. Berlin: Springer, pp. 49–69.
Fassbinder, J. W. E., and Gorka, T. H., 2009b. Vermessen? Das Römerkastell Burgsalach, Landkreis Weißenburg-Gunzenhausen, Mittelfranken. *Das archäologische Jahr in Bayern*, **2008**, 76–79.
Fassbinder, J. W. E., and Gorka, T., 2011. Magnetometry near to the geomagnetic Equator. In Drahor, M. G., and Berge, M. A. (eds.), *Archaeological Prospection: 9th International Conference on Archaeological Prospection, September 19–24, 2011, Izmir, Turkey*. Istanbul: Archaeology and Art Publications, pp. 45–48.
Fassbinder, J. W. E., and Irlinger, W. E., 1998a. Magnetometerprospektion eines endneolithischen Grabenwerkes bei Riekofen, Lkr. Regensburg. *Beiträge zur Archäologie in der Oberpfalz*, **2**, 47–54.
Fassbinder, J. W. E., and Irlinger, W. E., 1998b. Geophysikalische Prospektion in einem mehrphasigen Grabenwerk der Hallstattzeit auf dem Sandbuck bei Reinboldsmühle, Gemeinde Buxheim, Landkreis Eichstätt, Oberbayern. *Das archäologische Jahr in Bayern*, **1997**, 87–90.
Fassbinder, J. W. E., and Irlinger, W. E., 1999. Combining magnetometry and archaeological interpretation. In Fassbinder, J. W. E. (ed.), *Archaeological Prospection: Third International Conference on Archaeological Prospection; Munich 9.–11. September 1999*. München: Bayerisches Landesamt für Denkmalpflege. Arbeitshefte des Bayerischen Landesamtes für Denkmalpflege 108, pp. 95–99.
Fassbinder, J. W. E., and Stanjek, H., 1993. Occurrence of bacterial magnetite in soils from archaeological sites. *Archaeologia Polona*, **31**, 117–128.
Fassbinder, J. W. E., and Stanjek, H., 1994. Magnetic properties of biogenic soil greigite (Fe_3S_4). *Geophysical Research Letters*, **21**(22), 2349–2352.
Fassbinder, J. W. E., Stanjek, H., and Vali, H., 1990. Occurrence of magnetic bacteria in soil. *Nature*, **343**(6254), 161–163.
Fassbinder, J. W. E., Becker, H., and van Ess, M., 2005. Prospections magnétiques à Uruk (Warka). La cité du roi Gilgamesh (Irak). *Dossiers d'Archéologie*, **308**, 20–25.
Fassbinder, J. W. E., Bondar, K., Vogt, B., and Moser, J., 2009. Magnetometerprospektion und magnetische Eigenschaften von Basalt-Böden am Beispiel der Osterinsel (Isla de Pasqua), Chile. In Hauptmann, A., and Stege, H. (eds.), *Archäometrie und*

Denkmalpflege: Kurzberichte 2009; Zusammenfassung der Vorträge und Poster der Jahrestagung 2009. Bochum: Deutsches Bergbau-Museum. Metalla, Vol. 2, pp. 41–44.
Fassbinder, J. W. E., Narr, D., Linck, R., Deller, T., and Becker, F., 2011. Prospektion am römischen Kastell Großprüfening. *Das archäologische Jahr in Bayern*, **2010**, 92–95.
Fitzpatrick, R. W., and Le Roux, J., 1976. Pedogenic and solid solution studies on iron-titanium minerals. In Bailey, S. W. (ed.), *Proceedings of the International Clay Conference 1975, Mexico City, July 16–23, 1975*. Wilmette, IL: Applied Publishing, pp. 585–599.
Fröhlich, N., Posselt, M., and Schleifer, N., 2003. Excavating in a "blind mode". Magnetometer survey, excavation and magnetic susceptibility measurements of a multiperiod site at Bad Homburg, Germany. *Archaeologia Polona*, **41**, 167–169.
Gaffney, C. F., Gater, J. A., Linford, P. K., Gaffney, V. L., and White, R., 2000. Large-scale systematic fluxgate gradiometry at the Roman City of Wroxeter. *Archaeological Prospection*, **7**(2), 81–99.
Le Borgne, E., 1955. Susceptibilité magnétique anormale du sol superficiel. *Annales de Geophysique*, **11**, 399–419.
Le Borgne, E., 1960. Influence du feu sur les proprietes magnétiques du sol et sur celles du schiste et du granite. *Annales de Geophysique*, **16**, 159–195.
Lenz, J. E., 1990. A review of magnetic sensors. *Proceedings of the Institute of Electrical and Electronics Engineers*, **78**(6), 973–989.
Lovley, D. R., Stolz, J. F., North, G. L., Jr., and Phillips, E. J. P., 1987. Anaerobic production of magnetite by a dissimilatory iron-reducing microorganism. *Nature*, **330**(6145), 252–254.
Magnavita, C., and Schleifer, N., 2004. A look into the Earth: evaluating the use of magnetic survey in African archaeology. *Journal of African Archaeology*, **2**(1), 49–63.
Maher, B. A., and Taylor, R. M., 1988. Formation of ultrafine-grained magnetite in soils. *Nature*, **336**(6197), 368–370.
Maki, D. L., 2005. Lightning strikes and prehistoric ovens: determining the source of magnetic anomalies using techniques of environmental magnetism. *Geoarchaeology*, **20**(5), 449–459.
Mann, S., Sparks, N. H. C., Frankel, R. B., Bazylinski, D. A., and Jannasch, H. W., 1990. Biomineralization of ferrimagnetic greigite (Fe_3S_4) and iron pyrite (FeS_2) in a magnetotactic bacterium. *Nature*, **343**(6255), 258–261.
Möslein, S., 2002. Spätlatènezeitliche Umgangsbauten von Lerchenhaid, Stadt Straubing, Niederbayern. *Das archäologische Jahr in Bayern*, **2001**, 76–78.
Mullins, C. E., 1977. Magnetic susceptibility of the soil and its significance in soil science – a review. *European Journal of Soil Science*, **28**(2), 223–246.
Neubauer, W., and Eder-Hinterleitner, A., 1997. 3D-interpretation of postprocessed archaeological magnetic prospection data. *Archaeological Prospection*, **4**(4), 191–205.
Neubauer, W., Eder-Hinterleitner, A., Seren, S. S., Doneus, M., and Melichar, P., 1998–1999. Kombination archäologisch-geophysikalischer Prospektionsmethoden am Beispiel der römischen Zivilstadt Carnuntum. *Archaologia Austriaca*, **82**–**83**: 1–26.
Oldfield, F., 1992. The source of fine-grained 'magnetite' in sediments. *The Holocene*, **2**(2), 180–182.
Petersen, N., von Dobeneck, T., and Vali, H., 1986. Fossil bacterial magnetite in deep-sea sediments from the South Atlantic Ocean. *Nature*, **320**(6063), 611–615.
Scheffer, F., Meyer, B., and Babel, U., 1959. Magnetische Messungen als Hilfe zur Bestimmung der Eisenoxide im Boden. *Beiträge zur Mineralogie und Petrographie*, **6**, 371–387.
Schleifer, N., 2004. Ghost features – A proposal for appropriate management and a forum for discussion. *Newsletter of the International Society of Archaeological Prospection*, **1**, 6–9.
Schleifer, N., Fassbinder, J. W. E., Irlinger, W. E., and Stanjek, H., 2003. Investigation of an eneolithic chamer-group ditchsystem near Riekofen (Bavaria) with archaeological, geophysical and pedological methods. In Füleky, G. (ed.), *Soils and Archaeology, Papers of the 1st International Conference on Soils and Archaeology, Százhalombatta, Hungary, 30 May–3 June 2001*. Oxford: Archaeopress. British Archaeological Reports, International Series 1163, pp. 59–63.
Schmidt, A., 2002. *Geophysical Data in Archaeology: A Guide to Good Practice*, 2nd edn. Oxford: Oxbow Books.
Schmidt, A., Coningham, R., and Gunawardhana, P., 2009. At the equator: making sense of magnetomer data. *ArchéoSciences*, **33**, 345–347.
Schultze, V., Chwala, A., Stolz, R., Schulz, M., Linzen, S., Meyer, H.-G., and Schüler, T., 2007. A superconducting quantum interference device system for geomagnetic archaeometry. *Archaeological Prospection*, **14**(3), 226–229.
Schwertmann, U., 1988. Occurrence and formation of iron oxides in various pedoenvironments. In Stucki, J. W., Goodman, B. A., and Schwertmann, U. (eds.), *Iron in Soils and Clay Minerals*. Dordrecht: Reidel. NATO Advanced Science Institute Series C, Vol. 217, pp. 267–308.
Schwertmann, U., and Fechter, H., 1984. The influence of aluminum on iron oxides XI. Aluminum-substituted maghemite in soil and its formation. *Soil Science Society of America Journal*, **48**(6), 1462–1463.
Schwertmann, U., and Heinemann, B., 1959. Über das Vorkommen und die Entstehung von Maghemit in nordwestdeutschen Böden. *Neues Jahrbuch fur Mineralogie – Monatshefte*, **8**, 174–181.
Schwertmann, U., and Taylor, R. M., 1979. Natural and synthetic poorly crystallized lepidocrocite. *Clay Minerals*, **14**(4), 285–293.
Scollar, I., and Krückeberg, F., 1966. Computer treatment of magnetic measurements from archaeological sites. *Archaeometry*, **9**(1), 61–71.
Scollar, I., Tabbagh, A., Hesse, A., and Herzog, I., 1990. *Archaeological Prospecting and Remote Sensing*. Cambridge: Cambridge University Press.
Scotter, D. R., 1979. Soil temperatures under grass fires. *Australian Journal of Soil Research*, **8**(3), 273–279.
Stanjek, H., 1987. The formation of maghemite and hematite from lepidocrocite and goethite in a cambisol from Corsica, France. *Zeitschrift für Pflanzenernährung und Bodenkunde*, **150**(5), 314–318.
Stanjek, H., Fassbinder, J. W. E., Vali, H., Wägele, H., and Graf, W., 1994. Evidence of biogenic greigite (ferrimagnetic Fe_3S_4) in soil. *European Journal of Soil Science*, **45**(2), 97–102.
Taylor, R. M., Maher, B. A., and Self, P. G., 1987. Magnetite in soils: I. The synthesis of single-domain and superparamagnetic magnetite. *Clay Minerals*, **22**(4), 411–422.
Tite, M., 1966. Magnetic prospecting near to the geomagnetic equator. *Archaeometry*, **9**(1), 24–31.
Tite, M. S., and Linington, R. E., 1975. Effect of climate on the magnetic susceptibility of soils. *Nature*, **256**(5518), 565–566.
Tucker, P. M., 1952. High magnetic effect of lateritic soil in Cuba. *Geophysics*, **17**(4), 753–755.
Uda, M., 1965. On the synthesis of greigite. *American Mineralogist*, **50**, 1487–1489.
Van der Marel, H. W., 1951. Gamma ferric oxide in sediments. *Journal of Sedimentary Petrology*, **21**(1), 12–21.

Cross-references

Archaeomagnetic Dating
Electrical Resistivity and Electromagnetism
Paleomagnetism
Susceptibility

MASS MOVEMENT

John F. Shroder[1] and Brandon J. Weihs[2]
[1]Department of Geography and Geology, University of Nebraska at Omaha, Omaha, NE, USA
[2]Department of Geography, Kansas State University, Manhattan, KS, USA

Definition and introduction

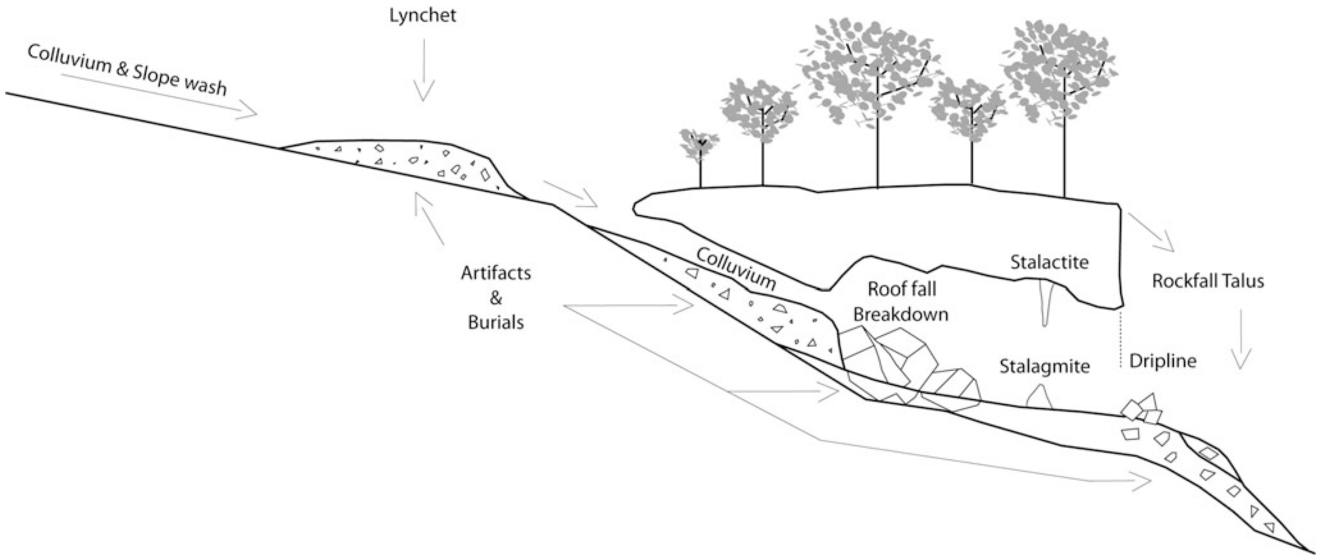
In the context of geoarchaeology, mass movement can be significant on several levels, including both site preservation and site disturbance. In some cases, catastrophic mass-movement events have altered local conditions, favorably or unfavorably, forcing ancient humans to change their land use patterns and thereby alter the archaeological record in important ways (Schruth and Pike, 2006; Pike, 2008). Mass movements and the forces that cause them can be complicated, but the diversity of physical processes involved must be understood by archaeologists at least on a fundamental level to enable better and more inclusive site interpretations. Furthermore, the future preservation of sites that have been newly exposed by excavation may be placed at risk by instabilities created by the digging itself or by the inherent nature of sites situated in vulnerable locations. In all such cases, improved understanding of mass-movement hazards at excavation sites may become necessary to preserve the site for posterity.

Mass movement is erosion, transportation, and deposition of earth and rock materials primarily as the result of gravity only, but it may include various admixtures of water, ice, and water vapor in the natural initial state. The term *mass wasting* is used by some; however, this term is considered somewhat outmoded by many, and it is ambiguous, leading to connotations that may erroneously include some aqueous slope wash. The more precise terminology of mass movement is much preferred. Human-made materials may be incorporated on, within, or beneath mass-movement deposits by various pre-, syn-, and post-event processes as well. Fluids are generally involved only minimally in mass-movement processes, and therefore sorting of particle sizes tends not to occur as it does with deposits laid down by water and wind. The result is that mass-movement events characteristically produce chaotic masses of mixed-up grain sizes and fragments, all of which can be considered collectively as colluvium. Most archaeological sites are similarly characterized by seemingly chaotic mixtures of different sizes of materials left by humans, who sort materials only when they are constructing things or depositing them consciously or not in spatially patterned ways. Otherwise the seeming chaos of most archaeological overburden may result from the relatively random combination of artificial and natural accumulations that cover sites slowly or quickly. Differentiating between small mass movements at a site and those produced directly by human activities may be difficult in some places. Scale-dependent process and product differentiation may be possible with attention to the details of mass-movement mechanics, especially where the mass movement was spatially large enough and temporally isolated to make its boundaries more easily recognizable.

Gravitative processes of mass movement are almost ubiquitous in many landscapes, and humanity has interacted with such environments repeatedly, leaving extensive records of such associations (James and Lecce, 2013). In some cases, mass movement established landforms that later provided shelter for humans, such as slope niches, overhangs, caves, and harbors. Both slow and more rapid processes of mass movement can affect the archaeological record in both preservative and destructive ways. For example, at the bottom of most slopes, various minor and slow gravitative movements of rocks and sediments – including slope wash or precipitation-induced sheet wash of fine sediment and frost-induced solifluction or gelifluction – may contribute thin layers of colluvium that build up successively to cover sites and artifacts (Figure 1). Older artifacts originally contained within sediments resting on slopes may be weathered out and moved downslope by these mass-movement processes and incorporated into newer colluvium, thus confusing and inverting the normal superposition of progressively younger layers covering older ones. An understanding of these fast or slow mass-movement mechanics will help the archaeologist interpret the original context of the archaeological site.

Archaeologically relevant mass-movement types

Mass movement is generally classified scientifically first by the type of material moved and second by the type of movement to which the material was subjected. The classification of mass-movement materials is simple in that only three categories are used: (1) rock and rock fragments that lie at one extreme, (2) fine-grained sediments (including sand, silt, and clay that collectively constitute "earth") that lie at the other, and (3) debris, which are composed of mixtures of both coarse rock fragments and fine clastics. The most rapid movements are falls, topples, slides, and the wetter, more fluid kinds of flow (mudflow, debris flow, volcano-sourced lahar flows). Slower forms of mass movement are subsidence, creep, solifluction (gelifluction), and earth flows. Talus is the one-by-one accumulation of rock fragments from isolated minor rock falls and slides that accumulate at the angle of repose in steep cones at the bases of cliffs and other steep slopes. All types of fast and slow mass movements can transport large quantities of sediment, moving artifacts, producing natural geofacts that resemble human-made artifacts, or burying archaeological sites. Colluvium is the general term for any kind of sediment emplaced by these gravitatively driven, mass-movement processes.



Mass Movement, Figure 1 Cross section through colluvia associated with surficial slope deposits and underground cave accumulations. Colluvium may accumulate downslope through long-term slope movements, slope wash, and ancient agriculture to constitute a positive or depositional lynchet, whereas the erosional area upslope that provides the material to build the positive feature may be the negative lynchet. Such lynchet terminology is characteristic of some European sites, but not necessarily elsewhere. Cave sites may accumulate colluvium carried in from outside through cracks and fissures, as well as from roof falls inside the cave or outside as a result of cliff collapse into a rockfall talus. Artifacts and burials can occur beneath the colluvium if the cultural activities occurred prior to mass movement or later as a secondary occupation or burial within the colluvium itself.

Creep

Creep is an imperceptible, slow, downhill movement of soil materials that generates plentiful colluvium in many archaeological sites. It includes the results of animals and humans trampling materials downward on slopes, as well as various downhill movements caused by the caving in of burrows created by fossorial animals, and plant-root expansion or collapses of plant-root decay cavities. In addition, creep can be produced by the ratcheting processes relating to phases of heating, wetting, and freezing of slope materials that cause an expansion outward and perpendicular to the hillslope gradient, followed by contraction phases brought on by cooling, drying, and thawing, all of which tend to result in net downward movement with gravity after each expansion-contraction cycle. Soil creep can have an important influence on the spatial distribution of artifacts by differentially transporting heavier or denser ones farther downslope than others, and if artifacts were originally deposited at the base of a slope, they can be buried by soil creep from upslope.

Colluviation and colluvium

All mass-movement processes can produce variable amounts of sediment known as colluvium, although the thinner varieties due mainly to creep at hillslope bottoms or footslopes are more commonly recognized in a geoarchaeological context. Typical hillslope cross sections consist of an upper stable interfluve of minimal declivity that passes outward and downslope into a zone of erosion with convex-upward seepage and creep slopes to a lower concave-upward transportational midslope. The lowermost zone of deposition is also concave upward in cross section and is characterized first by the colluvial footslope and the alluvial toeslope at the valley bottom. (See the nine-unit land-surface erosion model in the entry on colluvial settings.)

Colluvium from mass movement thus commonly forms hummocky topography or smooth fan-shaped deposits at the bases of mountains and hillslopes; they resemble, and may be intermixed with, alluvial-fan deposits that are predominantly caused by running water or sheet wash. Many colluvial soils can have an associated fragipan zone: brittle subsoil layers typically high in clay components. Such fragipans may result from the smearing of soils during the colluvial process wherein clays seal the surface between the moving fragipan and the stationary soil on which it slides. Archaeological sites can be buried and preserved beneath colluvium if changes in the landscape, e.g., deforestation or more extensive agriculture, lead to extensive downward movement of soil materials.

Identification of colluvial materials at archaeological sites can be problematic for the nonspecialist, and so checklists of features have been developed by the Soil Analysis Support System for Archaeology at the University of Stirling, UK (SASSA, 2009), that can be used in the field to determine the likelihood that a deposit could be considered to be colluvium:

- Landscape location of colluvium on footslopes, terraces, benches, floodplain edges, and valley-floor margins, or anywhere a break in slope occurs.
- Deposit matrix of colluvium can be slightly more silty and better sorted than deposits upslope, depending upon the processes by which the colluvium formed.
- Stones, potsherds, and charcoal in colluvium can have a weak tendency to align in the downslope direction.
- Softer potsherds and charcoal in colluvium may be worn and abraded.
- Common origin of colluvium from eroded topsoils can impart an organo-mineral composition and a brownish color.
- Colluvium should have a composition and stone lithology similar to soils upslope.
- Colluvial deposits should thin upslope and thicken toward the base of the slope.
- Colluvium may have less well-developed granular soil structures than non-disturbed topsoil materials, although periods of stability can allow reformation of granularity.
- Internal stratification and stone lines can form in colluvium.
- Lower boundaries of colluvium can be sharp or abrupt if not bioturbated by living organisms or heavily rooted.
- Clay coatings can occur in void spaces and on walls built of rock and sediment aggregations in colluvial materials.

Solifluction

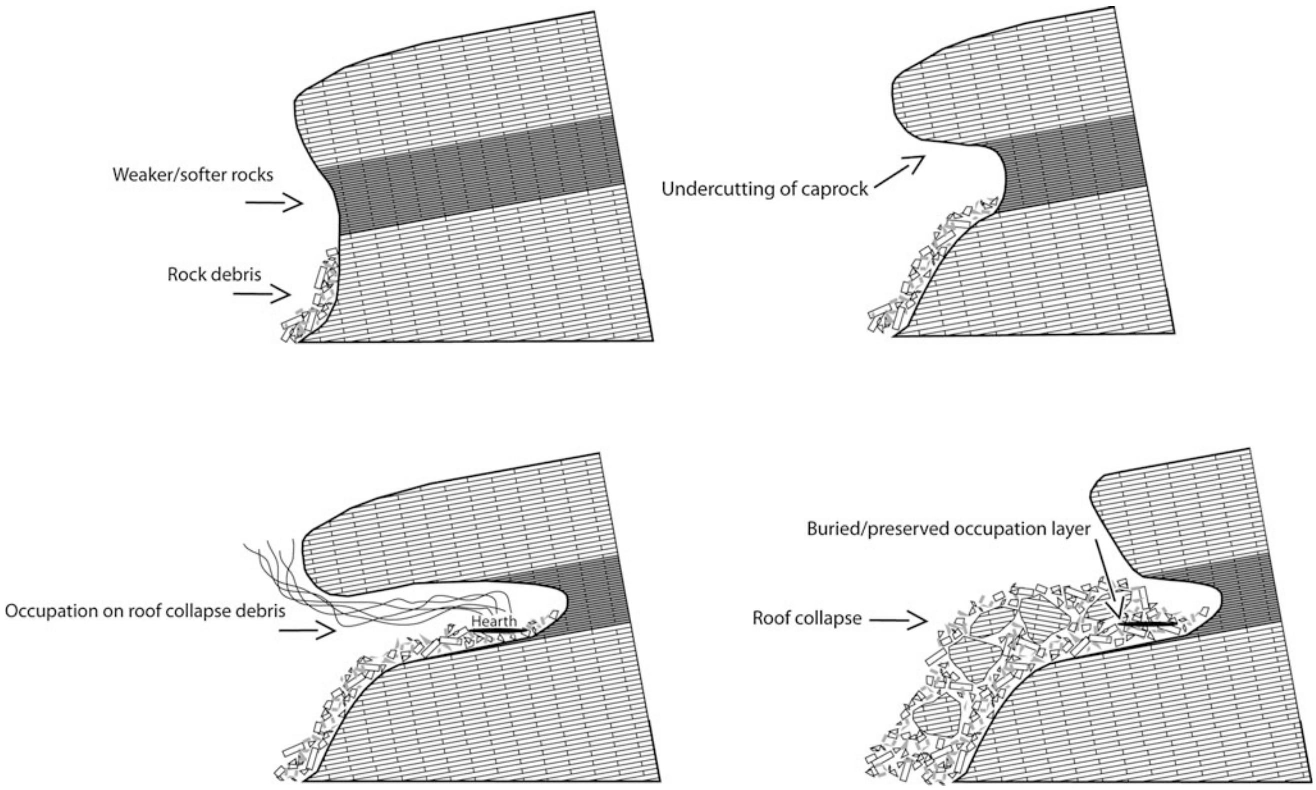
Solifluction results from strong freeze and thaw on slopes, commonly during the summer melt season. It describes masses of water-saturated debris moving downslope, commonly but not necessarily above permanently frozen deeper soils (Butzer, 1964; Goldberg and Macphail, 2006). Gelifluction, which is also understood as a form of solifluction, is the downslope movement of water-saturated sediments and soils that are generally associated with periglacial conditions in the seasonally thawed active layer above permafrost. Under these conditions of solifluction or gelifluction, major deformation of archaeological stratigraphic sequences can occur. Solifluction lobes can move downhill like the front end of bulldozer treads, creating a situation in which younger artifacts on the surface move forward across the top, past the advancing edge, and down the front as the lobe rolls over them on its way down the slope. Any stratigraphic sequence in the original soil is thereby reversed or inverted and no longer reflects the normal order of superposition with younger objects generally lying above older ones.

Early humans possessed a rich archaeological history in the Pleistocene Ice Age of Europe, and thus, their remains are commonly associated with extensive solifluction and related mass-movement deposits produced by high freeze and thaw. Deposits of unsorted and sorted rock rubble and sorted talus are the *éboulis ordonées* and *grèze litées* that are characteristic slope deposits in that region (Butzer, 1964). Such sorted rubble and talus slopes are caused by frost shattering on rocky slopes and cliffs, with subsequent downhill sliding of the resulting clastic sediment down slopes as shallow as 17 % (10°) and as steep as 60 % (35°). The fundamental mechanisms for the production of such bedded mass-movement deposits seem to be that first freezing in the spring breaks the rock debris and produces coarse beds of fragments that are well stratified and contain little or no interstitial material because the fragments slide over still-frozen soil. Thereafter, solifluction transports and deposits fines over the coarser materials, leaving multiple layers or stratifying the mass-movement beds.

Caves and overhangs

Early humans commonly sought shelter beneath overhanging rock-wall niches and in caves, and such locations therefore became living sites containing well-preserved archaeological remains (Figure 2). Many overhangs and caves include the deeper, dark interiors that were exploited for artistic and ritualistic activities, but most cultural material is located at the better illuminated cave mouths. Where archaeological material was deposited, however, it was always subject to burial and concealment by cave-roof falls of varying sizes (sometimes referred to as *éboulis* or rubble). The front edge or brow of the overhanging roof can produce a dripline, perceptible on the cave floor as a line representing the direct impact of precipitation falling from the top of the entrance. This location is the area of most active deadfall, where rock materials can also come down from slopes above. Talus and colluvium will accumulate downslope below the cave or rock-shelter entrance, and it is within this mass-movement material that cultural artifacts and other refuses (primary, secondary, de facto) from inside the cave will accumulate, including human burials in many cases (Figure 1).

Archaeological investigations of cave sites must take into account the likelihood that dramatic changes have occurred over time in which successive roof falls and retreat of the cave brow may have exposed ever deeper areas of the shelter to the forces of natural conditions outside the cave. The mouth of the cave may have been completely eliminated through roof collapses in the form of incremental mass-movement events. This can be documented by the series of driplines formed as the cave mouth receded (Figure 2). Many external fluvial, lacustrine, and aeolian processes can intercalate and intermix with the mass-movement sediments as well. In calcareous cave environments, the precipitation of dissolved calcium carbonate as layers of travertine flowstone (i.e., speleothems) can seal underlying cave sediments and artifacts. In some cases, unstable accumulations of cave bat and bird guano have themselves been remobilized to flow deeper into caves, forming additional mass-movement deposits (Dykes, 2007). In all cases of archaeologically significant cave stratigraphy, the stratification of sediments can be quite complex, and the elucidation of



Mass Movement, Figure 2 Four steps (*top left* to *lower right*) in the evolution of a typical shelter in limestone or other rocks where cave-roof collapse can preserve cultural materials and archaeological remains of the occupation layer beneath a cover of colluvium (in part after Rapp and Hill, 2006).

sequences containing intermixed materials deriving from a combination of gradual and mass-movement processes must be done carefully.

Special mass-movement erosion and deposition sites

In special cases, mass movements may figure importantly in the interpretation of archaeological sites, as when particular mass-movement actions effect landscape changes that offer advantageous settlement conditions for humans or where mass movements abruptly cover and seal important cultural remains. For example, in northern Israel, the gorge of the Jordan River north of the Sea of Galilee is geologically unstable. The Tuba I slope failure (>20,500 years ago) was perhaps generated by a strong earthquake (Shroder et al., 1999), and the large mass movement dammed the river, producing a lake that backed up within the gorge for many kilometers. As is common with most landslide dams across rivers, the impounded water eventually overtopped the dam causing a breakout flood that poured coarse gravels down upon the delta of the Jordan River at its entry into the northern end of the Sea of Galilee. This event established an irregular series of protected embayments composed of mass-movement gravels that were reworked by the breakout flood. It was here that ancient humans found a favorable setting to establish a coastal village over 5,000 years ago. This coastal fishing village grew over the ensuing millennia to become the important Biblical city of Bethsaida, a quiet-water port in which fine-grained low-energy muds accumulated directly at its edge. About 1,800 years ago, another landslide, the Tuba II slope failure, occurred within the Jordan River gorge and dammed the river once again. The ensuing re-impoundment of the Jordan River and failure of this second dam then brought coarse gravels from the landslide deposit via another breakout flood to the city and port of Bethsaida. This second mass-movement event proved to be a disaster in human terms, as it destroyed the protected anchorage, advanced the shoreline southward several kilometers, and eliminated the commercial value of the harbor to exploit the resources of the lake. With its chief fishing livelihood cut off, Bethsaida was ultimately deserted, and its exact location became lost until it was rediscovered in the late twentieth century (Arav et al., 2000).

Another example of mass movement having an archaeological impact occurs on the northern tip of the Olympic Peninsula in the state of Washington, USA. An ancient whaling village was established on the coast at Cape Alva by the Makah Native American people about 2,400 years ago with occupation lasting up to its final abandonment in the early twentieth century (Kirk, 1986; Samuels et al., 1991; Kirk and Daugherty, 2007). Radiocarbon dates of the oldest deposits recovered within archaeological exploration trenches dug below the long houses at the site indicated the great antiquity of the ancient village. Called the Ozette Site after a nearby lake of that name, the location was apparently overwhelmed by a mudslide that knocked the village flat and buried everything in deep, wet, preservative mud. The slope failure may have occurred about 300–500 years ago, and some think the date might be precisely on 26 January 1700 when a recorded earthquake occurred in the region. A substantial part of five large long houses from the village and all their contents were flattened and buried by the resulting mudslide or mudflow. The ten-foot-thick mass movement of wet clay pushed an airtight cover over the site and set up an anaerobic or oxygen-free environment that prevented the decay of all sorts of delicate organic materials that are rarely ever preserved in other burial environments. Delicate artifacts included harpoons, boats, kayaks, whistles, combs, gambling pieces, carvings, baskets, and artistic and/or ritualistic objects. Whale bones were recovered throughout the deposit, indicating the importance of the hunting of marine mammals to the ancient people.

Volcanic mass movements

Volcanoes and volcanic events preserve archaeological sites through ashfalls and other ejecta that may have nothing to do with mass movement. Lava flows, for example, commonly burn, crush, or pulverize and completely destroy most human-made structures before covering them with what becomes solid rock once everything cools. On the other hand, the common association of crater lakes and glaciers on high volcanic mountains provides plentiful water that can initiate rapid, wet volcanic mudflows, or lahars, from mobilized pyroclastic ash and other debris (Plunket and Uruñuela, 2008). The loose pyroclastic ash and cinders that accumulate in abundance on the flanks of most volcanic cones generally come to rest at steep angles of repose, and thus they are inherently unstable. During explosive eruptions, torrential rains can be unleashed by the atmospheric disturbance of the ash column above the volcano, and as the pyroclastic materials become saturated by the downpour, they can collapse producing enormous flows of muddy lahar material. The size and speed of such flows can be quite rapid, perhaps 40 m per second down the flanks of the volcano itself and perhaps 5–15 m per second as far as 50 km away. Most lahar masses are as destructive as lava flows because they resemble churning wet concrete as they sweep downslope, destroying everything in their path. Such material, once it dewaters and "sets up" after emplacement, can become quite indurated and hard, especially if it was once fairly hot as well. In rare cases, the result will be a thick, wet cover of hummocky volcanic debris that can quickly bury sites and preserve them for later archaeological excavation.

Scholars once thought that the ancient town of Herculaneum near Mt. Vesuvius had been buried by volcanic lahars rather than the loose tephra that buried Pompeii. This was because the material that covered Herculaneum had become almost rock hard, as mud would do over time. Present-day consensus, however, is that although a number of lahars did occur in the region, this volcanic mass-movement type was not the process that killed so many ancient Roman subjects and preserved their towns so well (Zeilinga de Boer and Sanders, 2002). Thus, only in a few places are lahars known to have been preservative of cultural remains. An example would be the rare exception of an old Native American settlement near volcanic Mt. Rainer, where the Osceola "mudflow" lahar overran the site to preserve numerous projectile points, scrapers, and other tools, as well as charcoal that gave a date of about 5,600 years ago (Harris, 1999). Many centuries elapsed before the native peoples reoccupied the site in a new settlement; their legends even allude to the tremendous lahar event (Stein, 2003).

Lahars do not always occur during volcanic eruptions; they can be set off at any time when torrential rains mobilize deposits of ash and loose rock. It is therefore difficult to make accurate predictions of lahar events, although general warnings are commonly issued. Volcanic eruptions demonstrate some predictability, as they are usually accompanied by precursory hints such as earthquakes, vents of steam and ash, and changes in the local water tables or in the height of the ground, but lahars can be triggered by a single day of heavy rain, which makes them a real danger in populated areas. Throughout history, lahars have destroyed many settlements, potentially rendering a few of them into deeply interred archaeological sites.

Mass-movement damage to archaeological sites

Mass movements of various kinds have negatively affected many archaeological sites in the past. They have occurred either as natural processes wherein sites established in unstable locations were partially destroyed (Stanley et al., 2006; Hartvich et al., 2007) or where the archaeological excavation itself resulted in the instability. In some cases, the very nature of the site is problematic, and special steps must be taken to preserve it from mass-movement damage – e.g., Machu Picchu, the Incan site in the Andes built atop steep cliffs (Vilimek et al., 2007). At Machu Picchu, a multidisciplinary approach has tried to discriminate between pre-habitation slope movements and those that occurred later up to the present time, as well as to evaluate landslide risk to existing structures. Elsewhere, Incan sites prone to landslide damage in Ecuador have been assessed using the techniques of satellite image analysis and geographic information system (GIS) analysis, including 3D visualizations and ortho-photo analyses to map site-specific hazards (Yugsi et al., 2006).

Another example of archaeological impact is Stutfall Castle, which represents the remains of a coastal Roman fort constructed about 270 CE near Lympne in extreme southeastern England. The fort was built on unstable Weald clay, and sometime following its construction, it was damaged by landsliding. The mass-movement event might have led to collapse of the fortress wall and therefore forced its abandonment. At present, all parts of the fort have been moved (at different times) from their original location, and the intact timber foundation piles beneath the rock walls have been bent and sheared off. Mapping of three main slope failure movements suggests that most of the slippage occurred after abandonment of the fort in the fourth century. A radiocarbon date of about 570 CE has dated the main slide mass that affected the site.

Similarly at the Celtic fortification site of Obři Hrad in the Šumava Mountains of Bohemia, in the Czech Republic, multigenerational slope deformation has disrupted the ancient site, probably multiple times in the past, and this has added to the complexity of site interpretation (Hartvich et al., 2007). Possibly, the ancient Celts established their fortifications purposefully in close proximity to the gods that were disrupting the ground, but in any case, the instability has eliminated parts of the site, the remains of which have been swept downslope ultimately to complete removal by the Losenice River below.

Conclusions

Mass-movement events can play integral roles in the preservation or destruction of archaeological evidence. Their wide spatiotemporal range and the physical properties and processes that govern their genesis and development have forced geoarchaeologists to consider the possibility of mass movement in almost any site setting, especially since its effects are so prevalent (in some cases disruptive and in others formative). Careful consideration of mass-movement processes will provide better explanations of site formation and use, and it will also help to preserve already excavated sites from damage by future movements.

Bibliography

Arav, R., Freund, R. A., and Shroder, J. F., Jr., 2000. Bethsaida rediscovered. *Biblical Archaeology Review*, **26**(1), 46–56.

Butzer, K. W., 1964. *Environment and Archeology*. Chicago: Aldine.

Dykes, A. P., 2007. Mass movements in cave sediments: investigation of a ~40,000-year-old guano mudflow inside the entrance of the Great Cave of Niah, Sarawak, Borneo. *Landslides*, **4**(3), 279–290.

Goldberg, P., and Macphail, R. I., 2006. *Practical and Theoretical Geoarchaeology*. Malden, MA: Blackwell.

Harris, S. L., 1999. Archaeology and volcanism. In Sigurdsson, H. (ed.), *The Encyclopedia of Volcanoes*. San Diego: Academic Press, pp. 1301–1314.

Hartvich, F., Zvelebil, J., Havliček, and Slabina, M., 2007. Multidisciplinary analysis of a slope failure at the Obři Hrad site in the Šumava Mts. *Geomorphologia Slovaca et Bohemica*, **7**(2), 47–57.

James, L. A., and Lecce, S. A., 2013. Impacts of land-use and land-cover change on river systems. In Wohl, E. (ed.), *Fluvial Geomorphology*. San Diego: Elsevier/Academic Press. Treatise on Geomorphology, Vol. 9, pp. 768–793.

Kirk, R., 1986. *Tradition and Change on the Northwest Coast: The Makah, Nuu-Chah-Nulth, Southern Kwakiutl, and Nuxalk*. Seattle: University of Washington Press.

Kirk, R., and Daugherty, R. D., 2007. *Archaeology in Washington*. Seattle: University of Washington Press.

Pike, S. H., 2008. Slope failure and the archaeological record of the Middle Sangro River Valley, Abuzzo, Italy: working towards an understanding of archaeological site formation, preservation and interpretation of high-relief Mediterranean valley systems. *Geological Society of America Annual Meeting, Houston, Texas, October 5–9, Abstracts with Programs*, **40**(6), p. 242, paper 188-12.

Plunket, P., and Uruñuela, G., 2008. Mountain of sustenance, mountain of destruction: the prehispanic experience with Popocatépetl volcano. *Journal of Volcanology and Geothermal Research*, **170** (1–2), 111–120.

Rapp, G. R., and Hill, C. L., 2006. *Geoarchaeology: The Earth-Science Approach to Archaeological Interpretation*, 2nd edn. New Haven: Yale University Press.

Samuels, S. R., Whelchel, D. L., Daugherty, R. D., and Mauger, J. E., 1991. *Ozette Archaeological Project Reports. volume 1. House Structure and Floor Midden*. Department of Anthropology Reports of Investigations 63. Pullman: Department of Anthropology, Washington State University; and Seattle: National Park Service, Pacific Northwest Regional Office.

SASSA, 2009. Soil Analysis Support System for Archaeology. http://www.sassa.org.uk/index.php/Main_Page

Schruth, C. L., and Pike, S. H., 2006. An investigation into the role of slope instability on archaeological site distribution and preservation in the Middle Sangro Valley, Abruzzo, Italy. *Geological Society America Annual Meeting, Philadelphia, Pennsylvania, October 22–25, Abstracts with Programs*, **38**(7), p. 214, poster no. 83–8.

Shroder, J. F., Jr., Bishop, M. P., Cornwell, K. J., and Inbar, M., 1999. Catastrophic geomorphic processes and Bethsaida archaeology, Israel. In Arav, R., and Freund, R. A. (eds.), *Bethsaida: A City by the North Shore of the Sea of Galilee*. Kirksville: Truman State University Press, Vol. 2, pp. 115–173.

Stanley, J.-D., Jorstad, T. F., and Goddio, F., 2006. Human impact on sediment mass movement and submergence of ancient sites in the two harbours of Alexandria, Egypt. *Norwegian Journal of Geology*, **86**(3), 337–350.

Stein, A. J., 2003. Osceola Mudflow from Mount Rainier inundates the White River Valley approximately 5600 years ago. HistoryLink.org; Encyclopedia of Washington State History; http://www.historylink.org/index.cfm?DisplayPage=output.cfm&file_id=5095

Vilímek, V., Zvelebil, J., Klimeš, J., Patzelt, Z., Astete, F., Kachlík, V., and Hartvich, F., 2007. Geomorphological research of large-scale slope instability at Machu Picchu, Peru. *Geomorphology*, **89**(3–4), 241–257.

Yugsi, F., Eisenbeiss, H., Remondino, F., and Winkler, W., 2006. Multi-temporal monitoring of landslides in archaeological mountainous environments using optical imagery: the case of El Tambo, Ecuador. In Campana, S., and Forte, M. (eds.), *From Space to Place: 2nd International Conference on Remote Sensing in Archaeology. Proceedings of the 2nd International Workshop, CNR, Rome, Italy, December 4–7, 2006*. Oxford: Archaeopress. British Archaeological Reports International Series, Vol. 1568, pp. 173–178.

Zeilinga de Boer, J. Z., and Sanders, D. T., 2002. *Volcanoes in Human History: The Far-Reaching Effects of Major Eruptions*. Princeton: Princeton University Press.

Cross-references

Archaeological Stratigraphy
Cave Settings
Colluvial Settings
Geographical Information Systems (GIS)
Geomorphology
Harbors and Ports, Ancient
Living Surfaces
Paleoenvironmental Reconstruction
Pompeii and Herculaneum
Radiocarbon Dating
Rockshelter Settings
Site Formation Processes
Site Preservation
Soil Stratigraphy
Speleothems
Trampling
Volcanoes and People

METALS

Vincent Serneels
Department Geosciences, University Fribourg, Fribourg, Switzerland

Metals, metal-bearing minerals, and ores

Metals are elements that are suitable conductors of heat and electricity. Most of them are malleable and shiny, but all other physical and chemical properties are highly variable. From the 98 elements naturally occurring on Earth, 73 are metals. An alloy has properties similar to a metal, but it is made of more than one element. Prior to the nineteenth century, only a limited number of alloys were in use, related to only six metals: gold, silver, copper, tin, lead, and iron. Other elements played a significant but specific role in ancient metallurgy: zinc, antimony, arsenic, platinum, nickel, and mercury. With the Industrial Revolution, new metals were introduced: magnesium, aluminum, titanium, manganese, chromium, nickel, cobalt, molybdenum, and tungsten.

The natural average abundance of metals within the continental crust of the Earth is quite variable (Rudnick and Gao, 2004). Aluminum and iron are major components, possessing an average of 8 % and 5 % by weight, respectively. The others are rarer: copper, zinc, and lead are in the range of 0.01–0.001 % (by weight); tin, silver, and gold are at 0.0001 % or even lower.

In rare cases, metals occur in the native form as solid metallic particles in nature. More often, metallic elements are trapped within minerals, e.g., oxides, sulfides, and carbonates (Klein and Dutrow, 2008), which necessitates a metallurgical treatment subsequent to mining in order to extract the metal (Higgins, 1993).

An ore is a natural rock containing a useful substance (element or mineral) that can be technically and economically exploited. The geological classification of ores is based on their formation processes (Guilbert and Park, 1986). The nature and grade of suitable ores are variable through time and space as technical and economical contexts evolve. An important parameter for the suitability of an ore is the concentration of valuable minerals within it, i.e., the ore grade. Simple processes like crushing, washing, and handpicking can sufficiently enrich the ore grade so that a crude ore coming out the mine contains more of the desired material when the concentrate is loaded into the furnace. In modern times, the tonnage of a deposit is as important as the ore grade itself to make an investment profitable, but this aspect was not that relevant during ancient times. Ores are nonrenewable resources, and their deposits are not equally distributed on Earth due to their tendencies to form in specific, well-defined geologic settings. With simple prospection methods, it is much easier to explore for ore deposits in mountainous areas and deserts, where the topography and the absence of soil provide a better chance to observe the outcropping ore.

Whatever the metal being worked, metallurgy can be presented as a production line (“chaîne opératoire”) involving raw materials (ore, fuel, refractories), means of production (manpower, energy, tools, and devices), skills and knowledge (practical and symbolic), and behavioral aspects. From a point of view restricted to technology, it is always a complex sequence with five main steps: extraction of the ore (mining), beneficiation of the ore (ore dressing), primary production of the metal (smelting), improving the metal quality (purification, alloying, etc.), and finally shaping of the functional object (casting, hammering). In addition, numerous techniques of decoration can be applied to metals, from simple engraving and punching to complex gilding. Metallurgy is a complex technology at the cutting edge of human knowledge.

History of metallurgical technology

From a worldwide perspective, the story of metallurgy is quite complex (Tylecote, 1992; Craddock, 1995). The first metals to be used were the ones naturally occurring as solid metal in the native state, i.e., copper, gold, and iron (Patterson, 1971). Lumps taken from sizable masses of native copper allowed the first metallurgists to experiment with the fundamental properties of metals: plastic deformation under hammering and melting at high temperature. The key role of native copper at the very beginning of metallurgy has been stressed (Wayman, 1989). Copper can be shaped by cold hammering and annealing at low temperature. It can also be melted in a crucible and afterwards poured into an open mold. The melting point is 1,083 °C, a temperature easily reached in a simple hearth by using a blowpipe or a bellows.

Searching for native copper opened the door to the discovery of ore smelting, i.e., the transformation of metal-bearing minerals into metal by the application of high temperature. Indeed, native copper occurs along with copper carbonates and oxides, which are easy to smelt.

Subsequently, smelting of mixed ores containing arsenic or antimony-bearing minerals led to the production of "natural" alloys that possessed more suitable physical properties than pure copper alone.

The cradle of metallurgy

In the Middle East, small objects made of native copper were already in use before 7000 BC. A few of them have been found at early Neolithic sites, like Çatalhöyük in Turkey, or Çayönü Tepesi, which lies farther east near the mines of Ergani (Maddin et al., 1991). It remains difficult to identify the oldest object made of smelted copper, but the process seems to have emerged around 6500 BC (Hauptmann and Weisgerber, 1996; Bourgarit, 2007).

Alloyed coppers are much harder than pure copper, and thus, they are more suitable for tools and weapons. Arsenic- and antimony-containing copper alloys were probably first produced by smelting naturally mixed ores containing those elements (Northover, 1989). The generalization of bronzes, the alloys of tin and copper, was a significant step leading to the Bronze Age ca. 3300–1200 BC. Except for a few deposits hosting the rare mixed mineral stannite, tin and copper minerals are not found together. Bronzes were deliberately obtained by mixing the two components. Tin is quite rare, especially in the Middle East (Yener, 2008; Yener et al., 2015). Thus, the search for tin became a strong motive for trading and long-distance exchanges (Penhallurick, 1986; Nezafati et al., 2006).

Gold and silver entered the archaeological record in significant fashion during the Bronze Age, with, for example, the magnificent treasure of Ur in Iraq at about 2600 BC (Bachmann, 2006), but earlier finds from cemetery remains in the Levant during the fourth millennium BC (circlets of gold and electrum, an alloy of gold and silver; see Gopher and Tsuk, 1996) and in Varna, Bulgaria, during the mid-fifth millennium BC (gold jewelry and other adornments from high-status Eneolithic burials; see Ivanov, 1978; Renfrew, 1978). Some of the oldest iron objects are nickel-rich, a typical chemical signature for meteorites (Waldbaum, 1980). Smelting of iron started at around 1400 BC by the Hittites in Anatolia (present-day Turkey).

Out of the cradle?

Recent archaeological work has modified our perception of the spread of metallurgy through the world. Traditionally, a diffusionist model has been favored, presenting the Middle East as the unique source area for metallurgical inventions in the Old World; however, the story is more complicated. Although the Middle East was an early and active spot for metallurgical works, inventions and improvements took place in many other areas, too. How these different places influenced each other is still a matter of debate.

The world's oldest gold objects have been found in the tombs of Varna, Bulgaria, which date to an age before 4000 BC (Kuleff, 2009). In this context, gold was already used as a prestige good with evident high social status significance (Renfrew, 1978). Excavations in Serbia indicate that the smelting of copper started at about 5000 BC in the northern Balkans without any obvious hints of influence from the Middle East (Radivojevic et al., 2010). In southern Spain, copper smelting started at around 3000 BC, but with a very primitive and non-slagging technology (Hook et al., 1991). At the same time, the technology of copper smelting was already much more evolved in the eastern parts of Europe (Strahm, 1994). It seems improbable that an already outdated technology had been imported. Some form of separate, Western reinvention process is more likely to have occurred. In Sweden, the earliest objects made of smelted iron are dated to 1200 BC (Hjärthner-Holdar, 2008). It is, therefore, difficult to merge these findings with the diffusionist model centered on Anatolia. The situation is probably similar regarding iron metallurgy in sub-Saharan Africa, although the early dates proposed (before 800 AD) still have to be confirmed (Alpern, 2005; Killick, 2009). No Bronze Age can be identified in most of the African archaeological record.

There is no doubt that metallurgy was invented independently in the Andean area (Peru and Bolivia). There, the use of gold started at about 2000 BC and spread after 1000 BC, giving rise to a range of peculiar gold alloys. There is evidence for copper ore smelting in the Moche culture on the coast of northern Peru (200 BC–600 AD) and later all over the Cordillera, even up to Western Mexico (Hosler, 1988; Shimada and Merkel, 1991). At about 850 AD, bronze alloys were produced in Bolivia, a region with deposits of tin ores. Iron smelting never appeared in pre-Columbian societies. In North America, the huge deposit of native copper on the Keweenaw Peninsula (Michigan, USA) provided metallic raw material to the native people from 3000 BC onwards (Childs, 1994). In this area, no ore smelting metallurgy is attested before contact with Europeans.

Some other significant steps in the development of metallurgy

About 2,000 years ago, only the fundamental metals (i.e., gold, silver, copper alloys, and iron) were part of the material culture of Europe and most of Asia and Africa. This situation changed dramatically with the onset of the Industrial Revolution. During the nineteenth century, the range of metals and alloys increased dramatically (Gille, 1978), and the tonnage of all kinds of metal production increased by several orders of magnitude. The industrial production of aluminum started during the twentieth century.

During the two millennia prior to the Industrial Revolution, many metallurgical improvements took place: low-grade sulfide copper ores were worked using the matte process, the production of brass by the cementation process was mastered, the difficult extraction of silver out of copper ores was solved by liquation with metallic lead, the use of mercury amalgam improved the recovery of gold, and so on (Tylecote, 1992).

The production of iron in the liquid state was a significant improvement. For more than 2,000 years, iron was obtained by the bloomery process in the solid state at low temperature and at low reduction rate (Rostoker and Bronson, 1990; Pleiner, 2000). The blast furnace producing molten cast iron was developed in the Rhineland during the Middle Ages, around 1300 AD. Cast iron is breakable and must be decarburized to obtain wrought iron (finery process). A further advance took place with the invention of the converter introduced by Bessemer (1850 AD), allowing the production of liquid steel. However, it should be noted that cast iron had been produced in China since 300 BC, much earlier than in Europe (Wagner, 2008). In general, the story about the development of metallurgy in India and China is quite different from that of the Western world. For example, the production of metallic zinc occurred much earlier in India, as it is attested in written sources from the first century BC and by archaeological evidence at Zawar from the twelfth century AD (Craddock, 1998).

The impacts of metals on human societies

The economic impact of metals on human societies is substantial. The need for utilitarian metals or the desire for precious ones is more intense in highly populated areas, i.e., areas suitable for agricultural production and human settlement. On the other hand, mountain belts or infertile deserts are the easiest places to find the ore deposits. Thus, the search for metals became a very strong factor in establishing exchange networks and contacts among different cultures. This process started during the Bronze Age but remained a trend throughout history. The Spanish conquest of the Americas and various gold rushes represent additional examples. There are numerous stories of booming cities directly related to mining, like Potosi (Bolivia), Goslar (Germany), and Jachymov (the Czech Republic).

Hard metals, mainly bronzes and steels, are the most suitable materials for the production of efficient weapons and tools. Primitive agricultural production based on slash-and-burn was much improved by the replacement of the Neolithic polished stone axe with one composed of bronze. Digging up the soil to introduce fresh nutrients by using a hoe or an ard significantly improved the production of food when iron cultivating implements became available for farmers. The introduction of more efficient iron plows during the Middle Ages in Europe brought similar consequences.

Efficient weapons ensure security and enhance military power. Good tools significantly improve the productivity of labor. Metal tools (chisels, axes, etc.) are the most efficient with which to work hard raw materials like metal, stone, or wood. The development of metallic machines during the Industrial Revolution greatly increased productivity again. In the modern world, metals become essential for machines, buildings, and transportation. The use of electricity is made possible by copper wires.

Precious metals, predominantly gold and silver, are not suitable for practical uses, but they gained a symbolic value and were used as prestige goods. Later, metallic coinage became the normal means for the payment of goods and services, increasing the demand for gold and silver. The search for precious metals is a quasi-universal and permanent driving force in human societies.

The impact of metals is not limited to the economy; there are also important social and cultural aspects. The production of metals, from the mine to the finished object, is a complex and sophisticated sequence of technical actions, with infinite variations depending upon the kind of ore, the technology, and the final product. The skills and knowledge required for a successful metal production line have to be highly developed, and they typically require a long apprenticeship. It has been argued that the development of metallurgy stimulated the process of specialization within prehistoric societies. In several cases, metallurgy became a prerogative of specialized social groups like the various endogamic groups of smiths in Africa (Tamari, 1997).

Metallurgy was efficiently practiced long before it was properly understood in the nineteenth century. The nature of metals had always been a matter of wonder and questioning for curious minds. The medieval alchemists are a good example of this intellectual endeavor, but there were classical Greek and Islamic predecessors, as well as the Chinese and Indian traditions. *De Re Metallica* ("On the Nature of Metals") written by Georgius Agricola (1556) is one of the most famous technical books of the Renaissance. Metallurgy is a strategic activity, always tentatively controlled by the social authorities and rulers via direct control, taxation, etc. Laws and regulation texts were already promulgated in early times.

Archaeometallurgy

Archaeometallurgy deals with all questions related to the production and use of metals during the past (Rehren and Pernicka, 2008; Killick and Fenn, 2012). For prehistoric periods, the archaeological record is the only source of information (Ottaway, 1994), but for the later, historic periods, illustrated, written, or even oral sources are available. Experimental archaeology – the modern replication of ancient technical processes under controlled conditions (Coles, 1979; Tylecote and Merkel, 1985) – and ethnological comparisons (Killick, 1991) also provide important information.

How, when, how much, and why metals have been produced and used are the basic questions addressed by archaeometallurgy. A wide range of methods has been developed to investigate these questions. The focus here will only be on the archaeological approaches and the contributions of natural sciences.

A first challenge for archaeometallurgical studies is the reconstruction of ancient technologies. There are always a number of ways to achieve a certain goal. To do things in a given way is a cultural choice influenced by technological constraints (Rehren et al., 2007), and therefore, the study of technologies is part of the study of cultures. In the pursuit of archaeometallurgical information, the archaeological record can be used to make detailed descriptions of production lines. Field data on the relevant archaeological remains (furnace design, site organization, etc.) must be combined with laboratory work (characterization of raw materials, waste, and products, estimates of temperature ranges, etc.). In this manner, it is possible to decipher the history of technology.

A second classical approach is the provenancing of metals. Much effort has been focused on developing methods to link a metal artifact to the geologic deposit from which its ore was originally mined, in the sense of geochemical sourcing. This knowledge can contribute significantly to a description of exchange networks and commercial contacts in the past. A third question is the location of major production centers in time and space and the quantification of production. Provenancing and quantification both contribute to the development of economic history.

Finally, archaeometallurgy aims to understand the impact of metals on societies and the environment.

The metallic objects

A first major source of information is the morphology of the metallic object itself. Typological and stylistic studies have always been performed, at least for well-preserved artifacts. More recently, small and degraded objects have also been analyzed. Beyond the interest in the object itself, however, the archaeological contexts of metallic finds are of crucial importance for understanding the way metals were used and discarded in the past.

With the development of metallography and other techniques for the chemical and physical characterization of metals during the late nineteenth century, specialists started to investigate the ancient materials themselves. A piece of metal can basically be characterized in two ways: by its chemical composition and by its physical structure.

Many methods can be used to measure the elementary chemical composition of a piece of metal using both bulk (XRF, AAS, PIXE, NAA, ICP-MS) and point (LA-ICP-MS, SEM, EPMA) analyses. Many of these methods are explained in other parts of this volume. There always is a risk in investigating small samples taken from large objects, as a representative result is not guaranteed. For metals, surface analyses are not recommended owing to possible corrosion. Measurements of the main elements are useful in specifying the type of alloy, but the minor and trace elements can provide information about the ores and metallurgical treatments. The elementary chemical composition of a metal is dependent upon the nature of the raw materials used, but it is dramatically affected by the metallurgical treatment. A copper object must have been made primarily from a copper ore, but all other elements initially present in the ore could have been removed totally or in part during the metallurgical treatment, while all the other elements present in the finished metal could have been introduced during the treatment. The interpretation of compositional data always requires good contextual knowledge. Despite those limitations, elementary chemical compositions provide fundamental information for the understanding of metallic objects. Trace elements are of particular interest for the study of copper-based alloys, both regarding their variability in ores and their influence on the metallurgical treatment (Junghans et al., 1968; Pernicka, 1998; Rapp et al., 2000). Current research focuses on nonmetallic micro-inclusions (slag) in bloomery iron for provenancing (Dillmann and L'Héritier, 2006; Schwab et al., 2006).

Much progress has been made in the measurement of isotopic chemical ratios in archaeological metals by means of mass spectrometry. Isotopic ratios that were present in the ore are not affected by metallurgical treatments, so they can be used for provenancing artifacts by comparing them to ratios found in the varied ores being tested. The main limitation of this technique arises when metalworkers in antiquity mixed metals, a quite frequent practice during recycling, which affects the isotopic ratios directly because objects from different sources may be combined. Nevertheless, the inherent variation of lead isotope ratios in ores is quite important and has been investigated in detail for many ore districts. Several successful studies based on isotopic ratios have been performed on lead, silver, and copper objects (Gale et al., 1980; Gale and Stos-Gale, 1982). A comprehensive example is a study of Bronze Age copper oxhide ingots found in the eastern Mediterranean Basin (Stos-Gale et al., 1997). The isotopic data pinpointed their origin on the island of Cyprus, mainly from the mine of Apliki. Copper, tin, and osmium isotopes are also used in provenance studies (Junk and Pernicka, 2003).

The physical structure of metal greatly influences the physical properties of an artifact. At the scale of the object, any defect such as a crack, a hole, or a deficient joint will likely be directly responsible for local weakness and breaking. At a microscopic scale, the size, shape, and distribution of crystals or grains will significantly affect physical properties, including hardness and ductility. The craftsman can control the microstructure during the production process: cold-working (hammering) decreases the grain size and increases hardness, while annealing (heating) increases the grain size. Characterization of the internal structure of a metal artifact can be done using X-ray radiography or tomography, but these techniques complement the more traditional optical observations, which involve metallographic reflected light microscopy and chemical etching on polished sections (Scott, 1991). These techniques are often accompanied by hardness measurements, scanning electron microscopy (SEM), or microprobe (EMPA) investigations.

Direct dating of metal artifacts remains very difficult. The presence of carbon from the fuel in steel and cast iron allows the use of the ^{14}C dating method (van der Merwe, 1969; Enami et al., 2004).

The production sites and their remains

Mining and metallurgical production remains and sites are the second type of evidence for archaeometallurgy. For a long time, these were overlooked by most archaeologists. In Europe, many ancient production sites of major importance were severely damaged during the intensification of mining activity in ore-bearing areas at the end of the nineteenth century, as recorded by several mining engineers of the period. The scientific archaeology of mining and metallurgy was established only during the 1950s. Archaeological field work, such as remote sensing surveys, excavation, and description of remains deliver much valuable information about dating, technology, size, and organization of metal production. Laboratory studies on wastes and debris, especially slag, supplement these field approaches.

Mining sites

During the nineteenth century, old galleries and ancient surface workings were observable in many active mines. A typical example is the Laurion district near Athens, Greece, where hundreds of pits and impressive slag heaps were observed (Ardaillon, 1897). These localities were involved in the extraction of silver during the classical period. For several decades, it was assumed that modern mining had destroyed everything (Davies, 1935), but during the last 30 years, this assumption has been completely reversed by new surface surveys and underground explorations conducted on ancient mines.

Several ores (gold, tin, iron) are present as particles or pebbles in superficial unconsolidated sediments. In the past, these placer deposits were attractive to miners because the ores are easy to recover. Extended fields covered by extraction holes 1–10 m in size are known for many periods and places. For example, at Vert-Saint-Denis, near Paris, France, more than 2,500 small pits for the extraction of iron ore were recorded during a rescue excavation (Daveau and Goustard, 2000). More intensive extraction can be managed with the help of running water within channels. Extensive surveys and archaeological work on the Iberian Peninsula revealed the large-scale development of superficial washing works of Roman and pre-Roman age at the square kilometer scale (Domergue, 1990). At the famous site of Las Medulas, Spain, a thick accumulation of poorly consolidated sediments containing low-grade gold was exploited by the so-called *ruina montium* technique described by Pliny the Elder, in his *Naturalis Historia* (N.H. 33, 66). First, shafts and tunnels were dug into the sediments. Afterwards, water, which had previously accumulated in large water tanks, was forced into the galleries to disaggregate the sediment. The volume of excavated material is estimated to have been up to 0.1 km^3.

Underground mining had already developed during prehistory, initially for flint but subsequently for metals. Bronze Age underground copper mines have recently been studied in Wales (Timberlake, 2003), Ireland (O'Brien, 2004), the Middle East at Timna, Israel (Conrad and Rothenberg, 1980), and at Faynan, Jordan (Hauptmann, 2007). Greek mining for silver at Laurion, Greece (Conophagos, 1980); Roman mining for silver and copper at Aljustrel, Portugal (Domergue, 1990); and medieval works for silver at Sainte-Marie-aux-Mines, France (Ancel and Fluck, 1988), are further examples of well-studied historical mining districts. Various marks on gallery walls help to discriminate formerly used techniques and tools, e.g., stone hammers, metal picks, or chisels, and use of fire. Water management is the most complex aspect of underground mining and a limiting factor in many cases.

The recent development of underground archaeological excavations brought exceptional finds to light, like in the Roman gold mines of Rosia Montana, Romania (Cauuet, 2008). Waterlogged galleries provide exceptional preservation conditions for supporting wood and machines.

Disposal of wasted rock outside of the mine entrance at the surface produces sizeable heaps. A mining landscape reveals not only varying amounts of extraction debris but also track ways, accesses, waste disposal areas, water channels and tanks, as well as additional settlements and buildings. In recent decades, the cultural importance of historical mining landscapes has been recognized, and several sites are now protected and valued as natural and cultural heritage. Some of them are on the UNESCO list of World Heritage Sites, such as the Roman gold mining field of La Medulas in Spain, the Engelsberg Ironworks in Sweden, the Rammelsberg mines in Germany, and the Blaenavon Industrial Landscape in the United Kingdom.

Solid knowledge of ore geology is of great importance in mining archaeology. For example, the variation of the ore grade at the scale of a meter can explain the complexity of the shape of old galleries. A detailed understanding of ore composition is required for the development of successful provenance studies. In many cases, the ancient exploitation started in the upper part of an ore deposit where the primary ore is usually transformed by supergene alteration and often appears at the surface as a highly oxidized staining of the local rocks by residual iron oxides (called gossan or eisenhut) after the main ore bodies have weathered. The upper-level ore minerals or rocks are very different from those mined deeper within the lode, as later operations at the same locality would discover. For example, during Roman times, the main ore at the Rio Tinto deposit in Spain was the silver-bearing jarosite, an uncommon sulfate mineral formed during the alteration process (Rothenberg and Blanco-Fereijeiro, 1981), but during the nineteenth century, Rio Tinto was the world's largest copper mine.

Ore dressing plants, in general, are located close to the mines. During ancient periods, the treatment of the ore was a combination of simple techniques based on crushing, washing, and handpicking. Flotation, lixiviation (leaching the desired solute from an ore using a solvent), and other chemical processes developed only recently. Some treatments can be performed with simple tools like a hammer, sieve, and bucket. More sophisticated equipment and machines were already in use during the classical periods, like the helicoidal washing plants of Laurion in Greece (Conophagos, 1980) and the rotary mills of Les Martys in France (Domergue, 1993). A complete medieval production line is illustrated by the drawings made by Heinrich Gross in 1529 at La Croix-aux-Mines in France (Brugerolles et al., 1992). Water channels and tank systems, heaps of crushed gangue (waste) rocks, and accumulations of fine-layered sediments are the typical remains of ore dressing plants (Bailly-Maître, 2010).

Remains of the extractive metallurgy

Slag heaps and furnace ruins are the characteristic indications of primary extractive metallurgy. Smelting sites in general are located close to the mines to minimize transportation of heavy loads of ore. Large quantities of fuel are also needed, and the location can be influenced by the proximity of wood or other burnable resources. In Europe, from medieval times onwards, water power has been used to run the bellows of large furnaces, and thus, plants have been built on riverbanks. In a few cases, metallurgists built their furnaces in specific locations to take advantage of particular conditions. For example, the iron furnaces driven by the monsoon winds in Sri Lanka are built just below the crest of hills where the wind is steady (Juleff, 1996). As a general rule, large smelting operations took place on specialized sites outside of settlements. The pattern of the distribution of the smelting sites illustrates the organization of production. Small-scale units can be scattered all over an extensive territory, or the activity can be centralized at a single large site with shared facilities. The distribution of production sites regarding the roads, waterways, farming estates, grouped settlements, and fortifications offers significant clues about the social system (Cleere, 1974; Jockenhövel and Willms, 2005; Rippon et al., 2009).

Early iron smelting sites called bloomeries are the most abundant and widespread for three main reasons. First, iron ores are abundant and widespread. Second, iron has been produced to a much higher scale than any other metal. Finally, the bloomery process produces large amounts of slag, and such slag heaps averaging 100,000 tons are known from the Roman period all over the Empire (Cleere, 1974; Domergue, 1993, 2008; Cech, 2008). Most of them were damaged or even totally recycled during the late nineteenth century when fayalite slag was fed into blast furnaces (Goudard, 1936; Pistolesi, 2006). Very large iron smelting sites are still preserved in many parts of the Sahel area in Africa (de Barros, 1986; Robion-Brunner, 2010; Serneels et al., 2012). Much smaller sites weighing in with a few tons of slag are quite numerous. Large slag heaps are the result of the dumping of wastes from furnaces that were reused many times, but single-use furnaces were also common, especially in northeastern Europe (Pleiner, 2000). The slag block formed inside such a furnace was left in the ground, and a new furnace was built adjacent to the first. Extended sites with hundreds of slag blocks have been investigated in the Holy Cross Mountain area of Poland (Bielenin, 1992).

There are spectacular remains of copper smelting, e.g., Faynan in Jordan (Hauptmann, 2007) and Cyprus (Kassianidou, 2000). Much work has also been done in the Alps (France, Italy, Austria) where significant Bronze Age production is evident (Cierny, 2008).

Sites and remains related to transformation metallurgy

For the production of metallic objects, the craftsman needs specific installations, including at the most basic level a hearth or furnace and a working bench or anvil. Many other features can be found at production sites, such as polishing facilities, water tanks, and fuel storage, and such workshops can be either simple and unspecific or highly specialized with sophisticated equipment. The metallurgical wastes, including slag, are characteristic of the type of work being conducted, and the quantities are always significantly less than the ones encountered at locations of extractive metallurgy. Areas where craft activities were performed are frequently found within large settlements, as such places permitted craftsmen to interact with consumers. Production of artifacts with new metal was only a part of the repertory of activities; recycling, repairing, and maintenance were also of major importance. Workshops were frequently grouped to form specialized districts within towns, and the metallurgical wastes produced in urban workshops were frequently used as embankment fill outside the working area.

From the Iron Age onwards, iron blacksmith workshops were common in the archaeological records of settlements. The normal range of smithing wastes from a single workshop is between a few kilograms and a few metric tons (Ottaway, 1992; Anderson et al., 2003). Many workshops for the production of nonferrous objects are known from historical periods (Chardron-Picault and Pernot, 1999), and as an example, a gold processing workshop found at Sardis in Turkey has been investigated in detail (Ramage and Craddock, 2000).

Common laboratory methods for the study of metallurgical wastes

There are not many precisely defined words that differentiate the types of waste produced during metallurgical activities (Bayley et al., 2008). Slag is a term that can refer to all kinds of waste that underwent at least partial melting. Another type of debris includes the ceramic materials involved in the metallurgical process, like furnace walls, air pipes (tuyères), molds, crucibles, cupels (for refining noble metals like silver through cupellation), and other vessels. Pieces of metal, at various stages of work, can usually be recovered at such sites. Hammerscales are small iron oxide particles formed at the surface of the hot metal in contact with the atmosphere; they are broken and scattered under the impact of hammer blows during smithing (Dungworth and Wilkes, 2007) and can be found within site sediments. Pieces of ore, additives or fluxes (limestone), and fuel (charcoal) can also be present. When the ancient smith operated with a well-mastered process, the nature of the waste tends to be constant, as the routines were automatic and repetitive. On the other hand, a poorly mastered process will yield variable wastes. In general, a single process will not give rise to one single type of waste but instead an assemblage of different wastes in more or less constant proportions.

All kinds of production waste can be investigated with the goal of material characterization (Bachmann, 1982; Serneels, 1993; Kronz, 1998; Fluzin et al., 2000; Bayley et al., 2008), and the methods listed for elemental or isotopic analysis of metals apply to slag and other wastes (see section on metallic objects above). In many cases, metallurgical wastes are found to be very heterogeneous. It is then important to investigate the structure and variability of the materials. Careful examination of the morphology and geometry of the waste is frequently key to understanding its significance and explaining the original metallurgical processes. In general, the structure of the slag at a grain-size scale reflects the cooling rate. The mineralogical composition can also give an estimate of the range of temperatures. Iron oxide, silica, and alumina are the most frequent chemical components; the most frequent minerals are fayalite (iron silicate), wüstite (iron oxide), and hercynite (iron aluminum oxide) (Bachmann, 1982, Serneels, 1993, Hauptmann, 2007).

For smelting slag, the chemical composition reflects the charge introduced into the furnace. The ore, constituting metallic minerals and unseparated gangue minerals, is always a predominant component of the charge, but fluxes and additives can be present. In many cases, high temperatures cause the partial melting of the furnace walls or the tuyères, and the resulting slags are contaminated. Finally, the fuel adds a significant amount of mineral matter into the furnace itself, predominantly calcium and potassium as ash.

It is a common approach to use phase diagrams to present chemical and mineralogical data on slag. Those diagrams are drawn from systems that reach a thermodynamic equilibrium, so they cannot be applied without caution to ancient metallurgical systems, which can be very far from equilibrium (Allibert and VDEh, 1995). In spite of this limitation, phase diagrams can help to assess the melting temperature and explain the relations between the ore, slag, and other components.

The composition of the gaseous atmosphere in the furnace is a key factor that affects the metallurgical treatments. The combustion of the fuel, mainly charcoal, controls the quantities of free oxygen, carbon monoxide, and carbon dioxide. The presence of more or less oxidized minerals in the slag is a useful indicator of the reduction rate, especially in the iron-oxygen system – metallic iron (Fe), wüstite (FeO), magnetite (Fe_3O_4), and hematite (Fe_2O_3).

There is no well-established method for the direct dating of fayalitic slag, and associated materials can be more suitable. Radiocarbon dating (^{14}C) is widely used on charcoal. In addition, thermoluminescence (TL) or even optically stimulated luminescence (OSL) can be applied to heated quartz grains embedded within industrial installations, such as the ceramic materials in furnace walls and tuyères, etc. Archaeomagnetic measurements can also be conducted on furnace and other heated clay structures found in situ.

Quantitative approach to metallurgical production

The qualitative approach to metallurgical remains aims to characterize the technology used and to define the different steps of the production line at a given archaeological site. A quantitative approach differs in that it attempts to evaluate the importance of the various past activities. Metallurgical remains are, with some restrictions, suitable for a quantitative approach, and as a general rule, there is a quantitative relation between the masses of slag, the amounts of ore processed, and the weight of metal produced.

In this respect, the simplest process is smelting: for a given amount of ore, a smelting operation will produce specific amounts of slag and metal (Eschenlohr and Serneels, 1991; Kronz, 2003; Crew and Charlton, 2007). The chemical data on ore, slag, and metal allow calculation of the ratio (mass balance calculation). The measure of the mass of slag allows an estimation of the masses of ore and metal involved. Hypotheses can then be formulated about the quantities of fuel and labor involved. The chemical composition of slag can be directly measured; however, it remains complex to define the composition of the ore. Sometimes, it is possible to sample the ore used from its geological position in the mine if such is known, but in most cases the crude ore underwent a process of beneficiation during production. A detailed topographic mapping can be used to evaluate the total volume of slag in remaining heaps (Decombeix et al., 1998). The mass of slag by unit of volume is directly weighed during trial excavation.

In many cases, quantification is difficult. If the metallurgical process was variable (including variability of the ore and the efficiency or quality of the product), no average calculation would be meaningful. Serneels and Perret (2003) present an example of a complex quantitative approach to a case of blacksmithing slag. An experimental approach is an alternative possibility to derive figures useful in comparison to quantification of archaeometallurgical sites (Crew, 1991), and ethnographical records offer a further option for obtaining similar comparative data (Bellamy, 1904).

Environmental approaches

Fuel studies

Fuel is involved in most metallurgical activities, as it is necessary for the production of heat. Carbon monoxide plays an active role in the reduction process. In most cases, the working temperatures are high (above 1,000 °C), and an efficient fuel is required (Rehder, 2000). Charcoal performs better than wood, and dense wood (hard) is better than lightwood (soft). High-quality coal is even better than charcoal. Before the Industrial Revolution, coal did not play a significant role in Europe. For the production of cast iron, the presence of sulfur in natural coals has long been a reason for rejection. The introduction of desulfurized coke obtained by distillation of coal by A. Darby at the beginning of the eighteenth century was an important advance during the Industrial Revolution. Other fuels, like turf or cow dung, have been of very limited use.

Species characterization of charcoal recovered from metallurgical sites and wood remains from mines offer interesting information about the natural environment of the sites, but they can also reveal practices of wood management, or even shortages (Py, 2006; Eichhorn et al., 2013). Dendrochronological approaches can provide significant data on seasonality or intensity of the labor (Pichler et al., 2013). Occasionally, wood or straw imprints on slag have yielded species identifications (Mikkelsen, 2003; Iles, 2009).

Paleopollution in soils, in sediments, and in ice cores

Metallurgical activities, with their high-temperature pyrotechnics, release significant quantities of dust and fine particles as an aerosol into the atmosphere. Geochemical anomalies of heavy metals, mainly lead, have been detected in ice cores drilled into the Greenland ice sheet. They are interpreted as an archive of ancient metallurgy at the global scale (Hong et al., 1994; Hong et al. 1996). Similar anomalies have been studied in peat deposits and lake sediments, mainly in the northern countries of Europe or in mountainous areas (Mighall et al., 2002; Shotyk, 2002). In the best cases, this type of record could reflect in detail the timing and the intensity of metallurgical activity. The data remain difficult to interpret, as the record is influenced by the superimposition of global and local signals and can be perturbed in many ways. Lead isotope measurements from aerosol particles can help to define the origin of the paleopollution (Dunlap et al., 1999).

Slag in stream sediments can be an interesting proxy leading to an understanding of the recent behavior of rivers and land use (Stolz and Grunert, 2008). Geochemical anomalies in archaeological sediments can reveal undetected metallurgical activity, and therefore, geochemical or geophysical measurements conducted during the excavation of workshop areas can provide significant information about the organization of local industrial activities. Several studies on smithing workshops pointed out the presence of hammerscale to identify the location of an anvil (Veldhuizen and Rehren, 2007). In the future, sedimentological methods, including micromorphology, could be applied successfully to ore dressing plant wastes and to soils of metallurgical workshops.

Summary

Metals are essential to human societies. For the production of tools and weapons, iron and copper-based alloys are the most efficient materials. Gold and silver were always used for prestige goods and later on for coinage. The oldest metal objects can be traced back before 7000 BC, but production at a significant scale started with the Bronze Age about 3300 BC and subsequently increased progressively. A peak in antiquity was reached around 100 BC in Europe, India, and China. The Industrial Revolution introduced several innovations, and production increased further during the nineteenth century.

Archaeometallurgy aims to reconstruct ancient technologies, past production patterns, and economies. This includes the study in the field of old mining works, large heaps of slag, furnace ruins, and archaeological traces of workshops, but it includes also the investigation of metallurgical wastes and artifacts in the laboratory. Historical period mining and metallurgy has had a significant impact on the environment (landscape change, pressure on fuel/wood resources, early pollution), but the use of metals has brought major advances to human societies, including the improvement of agricultural productivity, the development of craft specialization, and the accumulation of prestige goods.

Bibliography

Allibert, M., and VDEh/Verein Deutscher Eisenhüttenleute (eds.), 1995. *Slag Atlas*, 2nd edn. Düsseldorf: Verlag Stahleisen.

Alpern, S. B., 2005. Did they or didn't they invent it? Iron in sub-Saharan Africa. *History in Africa*, **32**, 41–94.

Ancel, B., and Fluck, P., 1988. *Une exploitation minière du XVIe s. dans les Vosges: Le filon Saint-Louis de Neuenberg (Haut-Rhin): caractères et évolution*. Paris: Editions de la Maison des sciences de l'homme. Documents d'archéologie française 16.

Anderson, T. J., Agustoni, C., Duvauchelle, A., Serneels, V., and Castella, D., 2003. *Des artisans à la campagne: carrière de meules, forge et voie gallo-romaines à Châbles (FR)*. Fribourg: Academic Press Fribourg, Editions Saint-Paul. Archéologie fribourgeoise 19.

Ardaillon, E., 1897. *Les mines du Laurion dans l'antiquité*. Paris: Editions A. Fontemoing.

Bachmann, H. G., 1982. *The Identification of Slags from Archaeological Sites*. London: Institute of Archaeology. Institute of Archaeology Occasional Publication 6.

Bachmann, H. G., 2006. *Mythos Gold: 6000 Jahre Kulturgeschichte*. München: Hirmer Verlag.

Bailly-Maître, M.-C., 2010. Extraction et traitement d'un minerai d'argent au Moyen Âge (XIIe–XIVe siècle). *Archeosciences, Revue d'Archéométrie*, **34**, 221–233.

Bayley, J., Crossley, D. W., and Ponting, M., 2008. *Metals and Metalworking: A Research Framework for Archaeometallurgy*. London: Historical Metallurgy Society. Historical Metallurgy Society Occasional Publication 6.

Bellamy, C. V., 1904. A West African smelting house. *Journal of the Iron and Steel Institute*, **2**, 99–126.

Bielenin, K., 1992. *Starozytne górnictwo i hutnictwo zelaza w Górach Swietokrzyskich*, 2nd edn. Kielce: Kieleckie Towarzystwo Naukowe. Ancient Mining and Iron Smelting in the Holy Cross Mountains (in Polish).

Bourgarit, D., 2007. Chalcolithic copper smelting. In La Niece, S., Hook, D., and Craddock, P. T. (eds.), *Metals and Mines: Studies in Archaeometallurgy*. London: Archeptype, pp. 3–14.

Brugerolles, E., Bari, H., Benoît, P., Fluck, P., and Schoen, H., 1992. *La mine mode d'emploi: la Rouge Myne de Saint Nicolas de la Croix*. Paris: Gallimard.

Cauuet, B., 2008. Equipements en bois dans les mines d'or protohistoriques et antiques (Gaule et Dacie romaine). In Bailly-Maître, M.-C., Jourdain-Annequin, C., and Clermont-Joly, M. (eds.), *Archéologie et paysages des mines anciennes: De la fouille au musée*. Paris: Picard, pp. 57–73.

Cech, B., 2008. *Die Produktion von Ferrum Noricum am Hüttenberger Erzberg*. Wien: Selbstverlag der Österreichischen Gesellschaft für Archäologie. Austria Antiqua 2.

Chardron-Picault, P., and Pernot, M., 1999. *Un quartier antique d'artisanat métallurgique à Autun, Saône-et-Loire: le site du Lycée militaire*. Paris: Editions de la Maison des sciences de l'homme. Documents d'archéologie française 76.

Childs, S. T., 1994. Native copper technology and society in eastern North America. In Scott, D. A., and Meyers, P. (eds.), *Archaeometry of Pre-Columbian Sites and Artifacts*. Los Angeles: The Getty Conservation Institute, pp. 229–253.

Cierny, J., 2008. *Prähistorische Kupferproduktion in den südlichen Alpen, region Trentino Orientale*. Bochum: Deutschen Bergbau-Museum. Der Anschnitt 22.

Cleere, H., 1974. The Roman iron industry of the Weald and its connexions with the *Classis Britannica. Archaeological Journal*, **131**(1), 171–199.

Coles, J. M., 1979. *Experimental Archaeology*. London: Academic Press.

Conophagos, C. E., 1980. *Le Laurium antique et la technique grecque de la production de l'argent*. Athens: Ekdotike Hellados.

Conrad, H. G., and Rothenberg, B., 1980. *Antikes Kupfer im Timna-Tal: 4000 Jahre Bergbau und Verhüttung in der Arabah (Israël)*. Bochum: Vereinigung der Freunde von Kunst und Kultur im Bergbau. Der Anschnitt 1.

Craddock, P. T., 1995. *Early Metal Mining and Production*. Edinburgh: Edinburgh University Press.

Craddock, P. T. Hrsg., 1998. *2000 Years of Zinc and Brass*, rev. edn. London: The British Museum. British Museum Occasional Paper 50.

Crew, P., 1991. The experimental production of prehistoric bar iron. *Historical Metallurgy*, **25**(1), 21–36.

Crew, P., and Charlton, M., 2007. The anatomy of a furnace . . . and some of its ramifications. In La Niece, S., Hook, D., and Craddock, P. T. (eds.), *Metals and Mines: Studies in Archaeometallurgy*. London: Archeptype, pp. 219–225.

Daveau, I., and Goustard, V., 2000. Un complexe métallurgique et minier du haut Moyen Âge. Le site des Fourneaux à Vert-Saint-Denis (Seine-et-Marne). *Gallia*, **57**(57), 77–99.

Davies, O., 1935. *Roman Mines in Europe*. Oxford: Clarendon Press.

de Barros, P., 1986. Bassar: a quantified, chronologically controlled, regional approach to a traditional iron production centre in West Africa. *Africa, Journal of the International African Institute*, **56**(2), 148–174.

Decombeix, P.-M., Fabre, J.-M., Tollon, F., and Domergue, C., 1998. Evaluation du volume des ferriers romains du domaine des Forges (Les Martys, Aude), de la masse de scories qu'ils renferment et de la production de fer correspondante. *Revue d'Archéométrie*, **22**, 77–90.

Dillmann, P., and L'Héritier, M., 2006. Slag inclusion analyses for studying ferrous alloys employed in French medieval buildings: supply of materials and diffusion of smelting process. *Journal of Archaeological Science*, **34**(11), 1810–1823.

Domergue, C., 1990. *Les mines de la péninsule ibérique dans l'Antiquité romaine*. Rome: Ecole française de Rome. Collection de l'Ecole française de Rome 127.

Domergue, C., 1993. *Un centre sidérurgique romain de la Montagne Noire: Le domaine des Forges, Les Martys, Aude*. Paris: CNRS Editions. Revue archéologique de Narbonnaise, supplément 27.

Domergue, C., 2008. *Les mines antiques: la production des métaux aux époques grecque et romaine*. Paris: Picard.

Dungworth, D., and Wilkes, R., 2007. *An Investigation of Hammerscale*. London: English Heritage. Research Department Report Series, Vol. 26.

Dunlap, C. E., Steinnes, E., and Flegal, A. R., 1999. A synthesis of lead isotopes in two millennia of European air. *Earth and Planetary Science Letters*, **167**(1–2), 81–88.

Eichhorn, B., Robion-Brunner, C., Serneels, V., and Perret, S., 2013. Iron metallurgy in the Dogon country (Mali West Africa)—"deforestation" or sustainable use? In Damblon, F. (ed.), *Proceedings of the Fourth International Meeting of Anthracology: Brussels, 8–13 September 2008, Royal Belgian Institute of Natural Sciences*. Oxford: Archaeopress. British Archaeological Reports, International Series, Vol. 2486, pp. 57–70.

Enami, H., Nakamura, T., Yamada, T., Tsukamoto, T., and Oda, H., 2004. AMS ^{14}C dating of iron artifacts: development and application. *Radiocarbon*, **46**(1), 219–230.

Eschenlohr, L., and Serneels, V., 1991. *Les bas fourneaux mé rovingiens de Boécourt, Les Boulies (JU, Suisse)*. Porrentruy: Office du patrimoine historique et Société jurassienne d'Emulation. Cahier d'archéologie jurassienne 3.

Fluzin, P., Ploquin, A., and Serneels, V., 2000. Archéométrie des déchets de production sidérurgique. *Gallia*, **57**(57), 101–121.

Gale, N. H., and Stos-Gale, Z. A., 1982. Bronze age copper sources in the Mediterranean: a new approach. *Science*, **216**(4541), 11–19.

Gale, N. H., Gentner, W., and Wagner, G. A., 1980. Mineralogical and geographic silver sources of Archaic Greek coinage. *Metallurgy in Numismatics*, **1**, 3–49.

Gille, B., 1978. La Révolution Industrielle. In Gille, B. (ed.), *Histoire des techniques: technique et civilisations, technique et sciences*. Paris: Gallimard. Encyclopédie de la Pléiade 41, pp. 677–771.

Gopher, A., and Tsuk, T., 1996. *The Nahal Qanah Cave: Earliest Gold in the Southern Levant*. Tel Aviv: Institute of Archaeology Publications. Monograph 12.

Goudard, A., 1936. Note sur l'exploitation des gisements de scories de fer dans le département de l'Yonne. *Bulletin de la Société archéologique de Sens*, **38**, 151–182.

Guilbert, J. M., and Park, C. F., Jr., 1986. *The Geology of Ore Deposits*. New York: Freeman.

Hauptmann, A., 2007. *The Archaeometallurgy of Copper: Evidence from Faynan, Jordan*. Berlin: Springer.

Hauptmann, A., and Weisgerber, G., 1996. The early production of metal in the Near East. In Bagolini, B., and Lo Schiavo, F. (eds.), *The Copper Age in the Near East and Europe. Colloquia of the XIII International Congress of Prehistoric and Protohistoric Sciences, Forlì (Italia) 8–14 September*. Forlì: Abaco Edizioni. Colloquia Series, Vol. 10, pp. 95–101.

Higgins, R. A., 1993. *Engineering Metallurgy. Pt 1. Applied Physical Metallurgy*, 6th edn. London: Arnold.

Hjärthner-Holdar, E., 2008. Iron production in bronze age Sweden. In Forenius, S., Hjärthner-Holdar, E., and Risberg, C. (eds.), *The Introduction of Iron in Eurasia: Papers Presented at the Uppsala Conference on October 4–8, 2001*. Uppsala: National Heritage Board, Department of Archaeological Excavations, Department of Archaeology and Ancient History, Uppsala University, pp. 9–15.

Hong, S., Candelone, J.-P., Patterson, C. C., and Boutron, C. F., 1994. Greenland ice evidence of hemispheric lead pollution two millennia ago by Greek and Roman civilizations. *Science*, **265**(5180), 1841–1843.

Hong, S., Candelone, J.-P., Patterson, C. C., and Boutron, C. F., 1996. History of ancient copper smelting pollution during Roman and Medieval Times recorded in Greenland Ice. *Science*, **272**(5259), 246–249.

Hook, D. R., Freestone, I. C., Meeks, N. D., Craddock, P. T., and Moreno Onorato, A., 1991. The early production of copper-alloys in South-East Spain. In Pernicka, E., and Wagner, G. A. (eds.), *Archaeometry'90: Proceedings of the 27th International Symposium on Archaeometry held in Heidelberg April 2–6, 1990*. Basel: Birkhäuser Verlag, pp. 65–76.

Hosler, D., 1988. Ancient west Mexican metallurgy: South and central American origins and west Mexican transformations. *American Anthropologist*, **90**(4), 832–855. NS.

Iles, L., 2009. Impressions of banana pseudostem in iron slag from eastern Africa. *Ethnobotany Research and Application*, **7**, 283–291.

Ivanov, I., 1978. Les fouilles archéologiques de la nécropole chalcolithique à Varna (1972–1976). *Studia Praehistorica*, **1–2**, 13–26.

Jockenhövel, A., and Willms, C., 2005. *Das Dietzhölzetal-Projekt: Archäometallurgische Untersuchungen zur Geschichte und Struktur der mittelalterlichen Eisengewinnung im Lahn-Dill-Gebiet (Hessen)*. Rahden: Verlag Marie Leidorf. Münstersche Beiträge zur Ur- und Frühgeschichtlichen Archäologie 1.

Juleff, G., 1996. An ancient wind-powered iron smelting technology in Sri Lanka. *Nature*, **379**(6560), 60–63.

Junghans, S., Sangmeister, E., and Schröder, M., 1968. *Kupfer und Bronze in der frühen Metallzeit Europas*. Berlin: Mann. Studien zu den Anfängen der Metallurgie 2.

Junk, S. A., and Pernicka, E., 2003. An assessment of osmium isotope ratios as a new tool to determine the provenance of gold with platinum group metal inclusions. *Archaeometry*, **45**(2), 313–331.

Kassianidou, V., 2000. Hellenistic and Roman mining in Cyprus. In Ioannides, G. K., and Hadjistyllis, S. A. (eds.), *Praktika tou Tritou Diethnous Kypriologikou Synedriou, Leukosia, 16–20 Apriliou 1996 [Acts of the Third International Congress of Cypriot Studies, Nicosia]*. Leukosia: Hetaireia Kypriakon Spoudon, pp. 745–756.

Killick, D., 1991. The relevance of recent African iron-smelting practice to reconstructions of prehistoric smelting technology. In Glumac, P. D. (ed.), *Recent Trends in Archaeometallurgical Research. MASCA Research Papers in Science and Anthropology 8, part 1*. Philadelphia: MASCA, University Museum, pp. 47–54.

Killick, D., 2009. Cairo to Cape: the spread of metallurgy through eastern and southern Africa. *Journal of World Prehistory*, **22**(4), 399–414.

Killick, D., and Fenn, T., 2012. Archaeometallurgy: the study of preindustrial mining and metallurgy. *Annual Review of Anthropology*, **41**(1), 559–575.

Klein, C., and Dutrow, B., 2008. *Manual of Mineral Science (after James D. Dana)*, 23rd edn. New York: Wiley.

Kronz, A., 1998. *Phasenbeziehungen und Kristallisationsmechanismen in fayalitischen Schmelzsystemen: Untersuchungen an Eisen- und Buntmetallschlacken*. Friedland: Klaus Bielefeld Verlag.

Kronz, A., 2003. Ancient iron production compared to medieval techniques in Germany: fayalitic slags and elemental mass balances. In Associazione Italiana di Metallurgia, *Archaeometallurgy in Europe, Proceedings of an International Conference, 24–26 September 2003, Milan, Italy*. Milano: Associazione Italiana Metallurgia, pp. 555–564.

Kuleff, I., 2009. Archeometric investigation of gold in the Chalcolithic necropolis of Varna (5th millennium BC). *Advances in Bulgarian Science*, **2**, 16–22.

Maddin, R., Stech, T., and Muhly, J. D., 1991. Cayönü Tepesi: the earliest archaeological metal artefacts. In Mohen, J.-P., and Eluère, C. (eds.), *Découverte du métal*. Paris: Picard, pp. 375–386.

Mighall, T. M., Timberlake, S., Clark, S. H. E., and Caseldine, A. E., 2002. A palaeoenvironmental investigation of sediments from the prehistoric mine of Copa Hill, Cwmystwyth, mid-Wales. *Journal of Archaeological Science*, **29**(10), 1161–1188.

Mikkelsen, P. H., 2003. Slag—with an impression of agricultural practices. In Nørbach, L. C. (ed.), *Prehistoric and Medieval Direct Iron Smelting in Scandinavia and Europe: Aspects of Technology and Society*. Aarhus: Aarhus University Press, pp. 43–48.

Nezafati, N., Pernicka, E., and Momenzadeh, M., 2006. Ancient tin: old question and a new answer. *Antiquity*, **80**, 308. Project Gallery.

Northover, P. J., 1989. Properties and use of arsenic-copper alloys. In Hauptmann, A., Pernicka, E., and Wagner, G. A. (eds.), *Archäometallurgie der Alten Welt: Beiträge zum Internationalen Symposium "Old World Archaeometallurgy," Heidelberg 1987. Der Anschnitt 7*. Bochum: Selbstverlag des Deutschen Bergbau-Museums. Veröffentlichungen aus dem Deutschen Bergbau-Museum Bochum 44, pp. 111–118.

O'Brien, W., 2004. *Ross Island: Mining, Metal and Society in Early Ireland*. Galway: Department of Archaeology, National University of Ireland, Galway. Bronze Age Studies 6.

Ottaway, P., 1992. *Anglo-Scandinavian Ironwork from 16–22 Coppergate, the Archaeology of York 17, fasc. 6*. London: Council for British Archaeology.

Ottaway, B. S., 1994. *Prähistorische Archäometallurgie*. Espelkamp: Marie Liedorf.

Patterson, C. C., 1971. Native copper, silver, and gold accessible to early metallurgists. *American Antiquity*, **36**(3), 286–321.

Penhallurick, R. D., 1986. *Tin in Antiquity: Its Mining and Trade Throughout the Ancient World with Particular Reference to Cornwall*. London: The Institute of Metals.

Pernicka, E., 1998. Whither metal analysis in archaeology? In Mordant, C., Pernot, M., and Rychner, V. (eds.), *L'atelier du bronzier en Europe du XXe au VIIIe siècle avant notre ère: 1, Les analyses de composition du métal*. Paris: Comité des travaux historiques et scientifiques (CTHS), pp. 259–267.

Pichler, T., Nicolussi, K., Goldenberg, G., Hanke, K., Kovács, K., and Thurner, A., 2013. Charcoal from a prehistoric copper mine in the Austrian Alps: dendrochronological and dendrological data demand for wood and forest utilisation. *Journal of Archaeological Science*, **40**(2), 992–1002.

Pistolesi, C., 2006. *La miniera di Baratti: Lo sfruttamento delle scorie etrusche dal 1915 al 1969*. San Giuliano Terme: Felici Editore.

Pleiner, R., 2000. *Iron in Archaeology, the European Bloomery Smelters*. Praha: Archeologický ústav AVCR.

Py, V., 2006. Mine charcoal deposits: methods and strategies. The medieval Fournel silver mines in the Hautes-Alpes (France). In Dufraisse, A. (ed.), *Charcoal Analysis: New Analytical Tools and Methods for Archaeology*. Oxford: Archaeopress. British

Archaeological Reports, International Series, Vol. 1483, pp. 35–46.
Radivojevic, M., Rehren, T., Pernicka, E., Šljivar, D., Brauns, M., and Borić, D., 2010. On the origins of extractive metallurgy: new evidence from Europe. *Journal of Archaeological Science*, **37**(11), 2775–2787.
Ramage, A., and Craddock, P. T., 2000. *King Croesus' Gold: Excavations at Sardis and the History of Gold Refining*. London: British Museum Press in association with Archaeological Exploration of Sardis, Harvard University Art Museums.
Rapp, G., Allert, J., Vitali, V., Jing, Z., and Henrickson, E., 2000. *Determining Geologic Sources of Artifact Copper: Source Characterization Using Trace Element Patterns*. Lanham: University Press of America.
Rehder, J. E., 2000. *The Mastery and Uses of Fire in Antiquity*. Montreal: McGill-Queen's University Press.
Rehren, T., and Pernicka, E., 2008. Coins, artefacts and isotopes—archaeometallurgy and *archaeometry*. *Archaeometry*, **50**(2), 232–248.
Rehren, T., Charlton, M., Chirikure, S., Humphris, J., Ige, A., and Veldhuizen, H. A., 2007. Decisions set in slag: the human factor in African iron smelting. In La Niece, S., Hook, D., and Craddock, P. T. (eds.), *Metals and Mines: Studies in Archaeometallurgy*. London: Archeptype, pp. 211–218.
Renfrew, C., 1978. Varna and the social context of early metallurgy. *Antiquity*, **52**(206), 197–203.
Rippon, S., Claughton, P. F., and Smart, C., 2009. *Mining in a Medieval Landscape: The Royal Silver Mines of the Tamar Valley*. Exeter: University of Exeter Press.
Robion-Brunner, C., 2010. *Forgerons et sidérurgie en pays dogon: Vers une histoire de la production du fer sur le plateau de Bandiagara (Mali) durant les empires précoloniaux*. Frankfurt: Africa Magna Verlag. Journal of African Archaeology Monograph Series, Vol. 3.
Rostoker, W., and Bronson, B., 1990. *Pre-industrial Iron: Its Technology and Ethnology. Archaeomaterials Monograph 1*. Philadelphia: Privately published.
Rothenberg, B., and Blanco-Fereijeiro, A., 1981. *Studies in Ancient Mining and Metallurgy in South-West Spain: Explorations and Excavations in the Province of Huelva*. London: Institute for Archaeo-Metallurgical Studies, University of London.
Rudnick, R. L., and Gao, S., 2004. Composition of the continental crust. In Rudnick, R. L. (ed.), *Treatise on Geochemistry*. Oxford: Elsevier-Pergamon, Vol. 3, pp. 1–64.
Schwab, R., Heger, D., Höppner, B., and Pernicka, E., 2006. The provenance of iron artefacts from Manching: a multi-technique approach. *Archaeometry*, **48**(3), 433–452.
Scott, D. A., 1991. *Metallography and Microstructure of Ancient and Historic Metals*. Los Angeles: The Getty Conservation Institute.
Serneels, V., 1993. *Archéométrie des scories de fer: Recherches sur la sidérurgie ancienne en Suisse occidentale*. Lausanne: Cahier d'archéologie romande. Cahier d'archéologie romande 61.
Serneels, V., and Perret, S., 2003. Quantification of smithing activities based on the investigation of slag and other material remains. In Associazione Italiana di Metallurgia, *Archaeometallurgy in Europe, Proceedings of an International Conference, 24–26 September 2003, Milan, Italy*. Milano: Associazione Italiana Metallurgia, pp. 469–478.
Serneels, V., Kiénon Kaboré, H. T., Koté, L., Kouassi, S. K., Ramseyer, D., and Simporé, L., 2012. Origine et développement de la métallurgie du fer au Burkina Faso et en Côte d'Ivoire. Premiers résultats sur le site sidérurgique de Korsimoro (Sanmatenga, Burkina Faso). *SLSA Jahresbericht 2011 (rapport annuel de la Fondation Suisse-Liechtenstein pour les recherches archéologiques à l'étranger)*. Zürich: Tamedia, pp. 23–54.
Shimada, I., and Merkel, J. F., 1991. Copper-alloy metallurgy in ancient Peru. *Scientific American*, **265**(1), 80–86.
Shotyk, W., 2002. The chronology of anthropogenic, atmospheric Pb deposition recorded by peat cores in three minerogenic peat deposits from Switzerland. *Science of the Total Environment*, **292**(1–2), 19–31.
Stolz, C., and Grunert, J., 2008. Floodplain sediments of some streams in the Taunus and Westerwald Mts., western Germany, as evidence of historical land use. *Zeitschrift für Geomorphologie*, **52**(3), 349–373. NF.
Stos-Gale, Z. A., Maliotis, G., Gale, N. H., and Annetts, N., 1997. Lead isotope characteristics of the Cyprus copper ore deposits applied to provenance studies of copper oxhide ingots. *Archaeometry*, **39**(1), 83–123.
Strahm, C., 1994. Die Anfänge der Metallurgie in Mitteleuropa. *Helvetia Archaeologica*, **25**, 2–39.
Tamari, T., 1997. *Les castes de l'Afrique occidentale: Artisans et musiciens endogames*. Nanterre: Société d'Ethnologie.
Timberlake, S., 2003. *Excavations on Copa Hill, Cwmystwyth (1986–1999): An Early Bronze Age Copper Mine within the Uplands of Central Wales*. Oxford: Archaeopress. British Archaeological Reports, British Series, Vol. 348.
Tylecote, R. F., 1992. *A History of Metallurgy*, 2nd edn. London: Institute of Materials.
Tylecote, R. F., and Merkel, J. F., 1985. Experimental smelting techniques: achievements and future. In Craddock, P. T., and Hughes, M. J. (eds.), *Furnaces and Smelting Technology in Antiquity*. London: The British Museum. Occasional Papers 48, pp. 3–30.
Van der Merwe, N. J., 1969. *The Carbon-14 Dating of Iron*. Chicago: The University of Chicago Press.
Veldhuizen, H. A., and Rehren, T., 2007. Slags and the city: early iron production at Tell Hammeh, Jordan and Tel Beth-Shemesh, Israël. In La Niece, S., Hook, D., and Craddock, P. T. (eds.), *Metals and Mines: Studies in Archaeometallurgy*. London: Archeptype, pp. 189–201.
Wagner, D. B., 2008. Chemistry and chemical technology, Part 11: ferrous metallurgy. In Needham, J. (ed.), *Science and Civilisation in China*. Cambridge: Cambridge University Press, Vol. 5.
Waldbaum, J. C., 1980. The first archaeological appearance of iron and the transition to the iron age. In Wertime, T. A., and Muhly, J. D. (eds.), *The Coming of the Age of Iron*. New Haven: Yale University Press, pp. 69–98.
Wayman, M. L., 1989. Native copper: humanity's introduction to metallurgy? In Wayman, M. L. (ed.), *All That Glitters: Readings in Historical Metallurgy*. Montréal: Canadian Institute of Mining and Metallurgy, pp. 3–6.
Yener, K. A., 2008. Revisiting Kestel mine and Göltepe: the dynamics of local provisioning of tin during the early bronze age. In Yalçın, Ü., Özbal, H., and Paşamehmetoğlu, A. G. (eds.), *Ancient Mining in Turkey and the Eastern Mediterranean*. Ankara: Atılım Universitesi, pp. 57–64.
Yener, K. A., Kulakoğlu, F., Yazgan, E., Kontani, R., Hayakawa, Y. S., Lehner, J. W., Dardeniz, G., Öztürk, G., Johnson, J., Kaptan, E., and Hacar, A., 2015. New tin mines and production sites near Kültepe in Turkey: a third-millennium BC highland production model. *Antiquity*, **89**(345), 596–612.

Cross-references

Archaeological Stratigraphy
Cave Settings
Colluvial Settings
Geographical Information Systems (GIS)
Geomorphology
Harbors and Ports, Ancient
Living Surfaces

Paleoenvironmental Reconstruction
Pompeii and Herculaneum
Radiocarbon Dating
Rockshelter Settings
Site Formation Processes
Site Preservation
Soil Stratigraphy
Speleothems
Trampling
Volcanoes and People

MICROSTRATIGRAPHY

Paul Goldberg[1] and Richard I. Macphail[2]
[1]Department of Archaeology, Emeritus at Boston University, Boston, MA, USA
[2]Institute of Archaeology, University College London, London, UK

Definition

The study of sedimentary deposits at the mm to cm scale.

Introduction

A concept of major importance to both the earth sciences and archaeology is that of stratigraphy. Stratigraphy has many "*definitions*," and a typical one can be expressed as simply: "[the] scientific discipline concerned with the description of rock successions and their interpretation in terms of a general time scale" (Encyclopædia Britannica online, 2012). A more informative and broader *characterization*, which is suitable to a geoarchaeological audience, might be: the geometrical, spatial, and temporal arrangement of rocks, deposits, soils, and archaeological features (e.g., architecture, hearths). For predominantly historical reasons, geologists have erected a variety of operationally and conceptually independent stratigraphic strategies within the realm of stratigraphy; these include lithostratigraphy, biostratigraphy, magnetostratigraphy, chronostratigraphy, and soil stratigraphy (e.g., Gilbertson, 1995). Such approaches are needed in order to correlate (i.e., demonstrate physical or temporal equivalence) different objects and deposits encountered in a geoarchaeological context.

Typically, stratigraphy is intellectualized at a variety of scales, including that of geological landscapes (e.g., the state of New York), an exposure in a single area (e.g., within the Grand Canyon), or an outcrop. In archaeology, stratigraphy is normally envisioned at the site scale, be it a Middle Eastern tell or that exposed in excavation of a Neanderthal encampment in France. Geoarchaeologists need to be conformable about working at several scales, which commonly overlap: conducting a regional search for rocks involved in sourcing raw materials or attempting to understand the nature and origin of a "mousey brown" layer exposed in the corner of an excavated building.

Related to the idea of stratigraphy is that of facies, which can be considered as the "physical, chemical, and biological aspects of a sedimentary bed and the lateral change within sequences of beds of the same geologic age" (Encyclopædia Britannica online, 2012). Thus, within a deltaic deposit, we can observe various lithologies depending on the location (e.g., beach, channel, swamp, distal bar). Facies is an important concept because it allows us to monitor different, spatially contiguous and contemporaneous lithologies that represent subenvironments of the same depositional system.

In geology, the notion of facies has been extended to the study of deposits at a finer, mm to cm scale. Microfacies, "…the total of all sedimentological and paleontological data which can be described and classified from thin sections, peels, polished slabs or rock samples" (Flügel, 2004, 1), is an invaluable tool for conceptualizing and examining stratigraphy at a fine scale, i.e., microstratigraphy. Microstratigraphy, then, is no different in principle from stratigraphy as employed on a geological scale, except that the primary focus is lithostratigraphy, which describes packets of deposits based on similar lithological criteria such as color, texture, grain size, structure, and consistence. In addition, microstratigraphy may be delineated on the basis of different microfossils (e.g., diatoms and foraminifer) in marine and coastal environments, or pollen in waterlogged terrestrial environments. In geoarchaeology, microartifacts recovered by sieving, or identified and counted in thin section, also contribute to understanding microfacies (Rosen, 1993; Sherwood et al., 1995).

Methods used in microstratigraphy

Microstratigraphy is studied both in the field and in the laboratory. Field approaches entail detailed observations of the microstratigraphy, including vertical and lateral facies changes. At the same time, the stratigraphic units are documented by careful drawings and detailed photographs of the deposits; flash photography is particularly useful as the flash can enhance contrast and make subtle stratigraphic units much more visible. In addition, archives of the deposits can be produced by employing sediment peels (Goldberg, 1975), a technique borrowed from geology.

Once microstratigraphic units have been identified and characterized, they can be sampled for subsequent work in the laboratory. The most appropriate sampling strategy at the outset is to collect undisturbed blocks for micromorphological analysis (Goldberg and Macphail, 2003) (see entry on Soil Micromorphology). At the same time, bulk samples from individual microstratigraphic units can be taken, carefully noting their relationship to the block sample and the overall microstratigraphic sequence. Such "microbulk" samples are very useful undertaking bulk analyses on loose sediments, such as grain size, bulk chemistry, magnetic susceptibility, etc.

In the laboratory, block samples are dried and impregnated with resin (polyester or epoxy) and processed into petrographic thin sections and observed under the polarizing light microscope (Courty et al., 1989). Although micromorphological analysis provides a very effective means of characterizing the deposits (e.g., composition, texture, and their three-dimensional arrangement: fabric) and revealing the interplay between depositional and postdepositional geogenic and anthropogenic processes, it has its limitations in identifying the nature of inorganic and organic small (say, fine silt and smaller) particles, including mineralogy, organic composition, and degree of heating of a material. Thus, additional "microstratigraphic" techniques are required to yield such information (Artioli, 2010; Weiner, 2010). These techniques can include Fourier transform infrared spectrometry (FTIR; and micro-FTIR, which enables identification of materials contextualized within the thin section itself (Goldberg and Berna, 2010); see entry), x-ray diffraction (see entry on X-ray Diffraction (XRD)), Raman spectroscopy, and scanning electron microscopy (SEM) or microprobe, both of which can provide microelemental analyses (see Figures 7 and 8). In addition, bulk chemical analyses (e.g., Parnell and Terry, 2002; Barba, 2007) and magnetic susceptibility (Crowther, 2003) can be performed on the microbulk samples that were collected at the same time as the undisturbed micromorphology blocks.

Application of microstratigraphy to geoarchaeology

Unlike geological microstratigraphy, archaeological microstratigraphy takes into consideration the artifacts of humans and site formation processes brought about by them. Context units and subunits can therefore be partially or wholly the product of human activity. In many readily understood and well-studied Quaternary sites, natural physical and chemical effects often predominate, but in anthropogenic deposits and occupation surface formations, especially within settlements of complex societies, sedimentary processes may well be totally anthropogenic. In the case of the French Middle Paleolithic site of Pech de l'Azé IV, for example (see entries on "Rockshelter settings" and "Site Formation Processes"), natural cave sediments are intercalated with combustion zone deposits, as well as lithic and faunal remains (Figures 1 and 2). Natural cave sediment formation processes often play a secondary role in such contexts and in this example include localized phosphatization. In other Paleolithic cave and rock-shelter deposits in France, for example, geogenic deposits can be more prominent (e.g., Laville et al., 1980; Texier et al., 2004)

The Upper Paleolithic site of Chongokni, Hantan River, Republic of Korea, in the Imjin River Basin, is characterized by Acheulean-like hand axes, with new charcoal dates, which suggest that some 10 m of alluvium accumulated over 30 kyr (Seonbok Yi, Seoul National University, pers. comm.). Such rapid sedimentation makes it very difficult to differentiate alluvial site formation

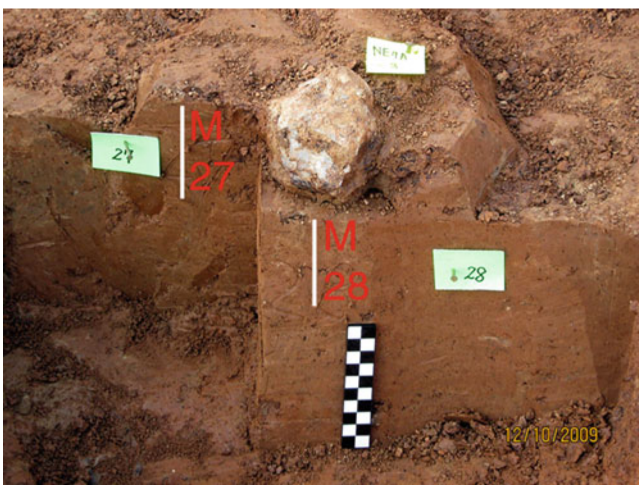
Microstratigraphy, Figure 1 Layer 8 from the French Middle Paleolithic site of Pech de l'Azé IV, showing the remains of both intact combustion features with ashes (*white band*) and those that have been modified by trampling and rake-out (redistribution of combusted material in cleaning and preparation for new fires).

"noise" from information associated with paleoenvironmental reconstruction of the land surface associated with the presence of hominid activities. This challenge was mitigated by sampling beneath and next to the artifacts (Figure 3). Large artifacts such as hand axes and quartzite cores protected sediment that is immediately beneath them. At one example, the microstratigraphy is composed of bedded microlaminated wet season alluvium; here silts occur with eroded clasts of clayey soil (Figures 4 and 5, "Bsed"). Immediately below the quartzite core, the alluvium becomes worked by soil fauna and rooting plants (Figure 6). Thus, in theory, a thin homogenized entisol (a young soil) had briefly formed during the dry season, and it was during this season that hominids traveled this landscape and at this location discarded a quartzite core. It can also be noted that within this microstratigraphic sequence it was important to recognize the hierarchy of the features, notably that:

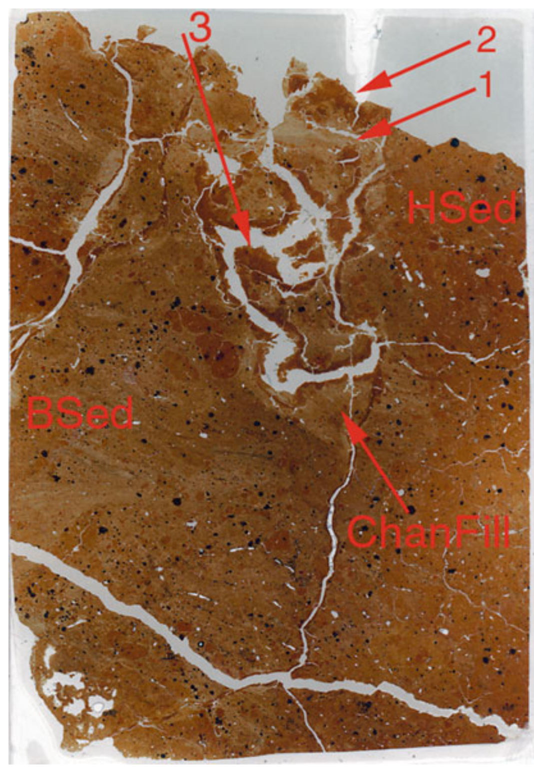
1. Bedded alluvium came first ("Bsed").
2. Followed by surface soil homogenization (Hsed).
3. The quartzite core was discarded (Figure 3).
4. Finally, renewed alluviation led to inwash of clay ("ChanFill").

As suggested above, the microstratigraphy of deposits in complex societies can be much more complicated, as they form mostly through human activities, such as dumping, sweeping, and trampling. Thus, they can reflect different activities through space and time and not different natural environments. They still produce diverse types of microfacies, however, that can be interpreted in terms of activities and use of space (Courty, 2001). A major site

Microstratigraphy, Figure 2 Microstratigraphic sequence from Middle Paleolithic deposits at Roc de Marsal, France. Some of the stratigraphic units are depicted here with *green* numbers. (*1*) Reddish silty clay formed in pockets above the bedrock. (*2*) Dispersed remains of combustion feature, locally phosphatized. (*3*) Band of intact and reworked combustion features; *yellow arrow* points to erosional contact with unit 4. (*4*) Stony clayey silt rich in bones. (*5*) Partial remains of combustion features with sharp, erosional contact with the overlying layer 6 (*yellow arrow*). (*6*) Similar to layer 4 but occurs as lens with upper, erosional contact with layer 7 (*red arrow*). (*7*) Stony clayey silt with charcoal and organic matter.



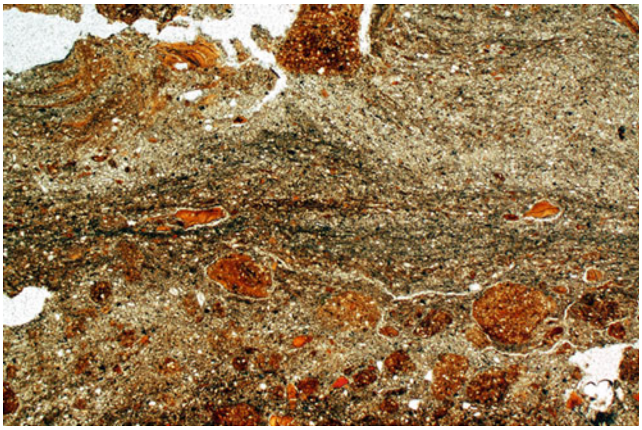
Microstratigraphy, Figure 3 Upper Paleolithic Chongokni, Hantan River, Republic of Korea; quartzite core sample, core-buried protected soil sample M28, and unburied soil surrounding quartzite core sample M27 (NE 07A) (Courtesy of Seonbok Yi, Seoul National University).



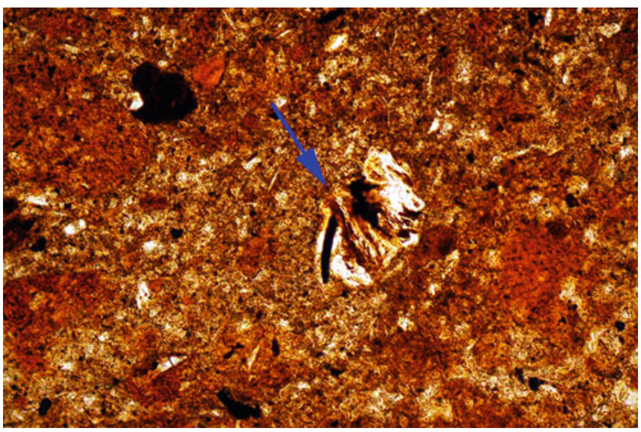
Microstratigraphy, Figure 4 As Figure 3; scan of M28, showing pre-quartzite core-bedded fluvial sediments (Bsed) and the biologically homogenized soil-sediments (Hsed) that had developed in them (also 2). This alluvial entisol probably formed during the post-wet season period and just before the cobble was deposited. The next wet season's rainfall led to subsurface (sub-core) channeling or "tunneling." The channel then became infilled (ChanFill) with silts (see also 1). Finally low-energy alluvial clay-infilled cracks in the fill (3). Frame width is ~50 mm.

formation model proposed by Gé et al. (1993) attempted to characterize a specific type of anthropogenic sediment related to occupation "floors" and their origin. Passive, active, and reactive zones were identified in accordance with their original constituents and the physical effects of trampling on the floor surfaces. Additional aspects considered were open-air sites, roofed sites, and how different material and moisture contents affected the character of the sediment at these complex sites (Courty et al., 1994, Table 1).

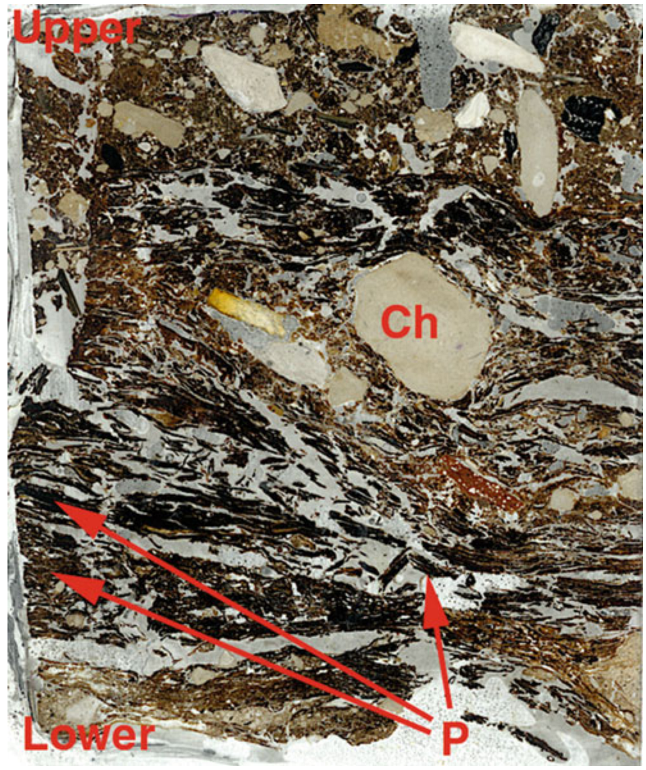
More recently, additional analytical approaches have been developed to help characterize occupation deposits.



Microstratigraphy, Figure 5 As Figure 4, photomicrograph of "Bsed," laminated alluvial silts and eroded clay clasts, the surface of which became biologically homogenized probably over one season (see Figure 6) before the quartzite core was discarded (?). Plane-polarized light (*PPL*), frame width is ~4.62 mm.



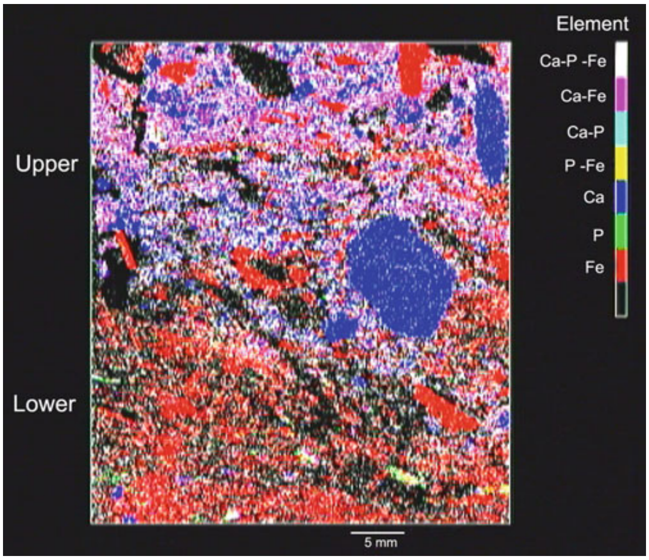
Microstratigraphy, Figure 6 Photomicrograph of pre-core homogenized "entisol" (Hsed) formed in possibly months after fluvial deposition of bedded silty clay (Bsed) and before core was "dropped" (see layer 2, Figure 4). Note ferruginized root section (*arrow*, *center*) and fragments of hematite-iron clay (XRD). PPL, frame width is ~0.9 mm.



Microstratigraphy, Figure 7 Pilgrims' School, in the environs of Winchester Cathedral, UK (Courtesy of Oxford Archaeology South). Scan of M309B (14th C Context 309); anomalously humic (34.4 % LOI), enriched in both phosphate (3.92 mg g-1 P) and lead (736 μg g-1 Pb), with very rich pollen content of cereals, grasses, and herbs. Frame width is ~50 mm.

One approach includes the measurement of magnetic susceptibility (χ). For example, a constructed floor may have an enhanced χ because its composition includes burned mineral material, and/or because it was heated in situ, as in a hearth or near-hearth location. Equally, phosphate may be high, but again this may be due to included fragments of bone and coprolites or to secondary phosphate migration. The same applies to heavy metal contamination. In all these cases, different methodologies need to be used – including soil micromorphology, bulk soil analyses of the microstratigraphic units and ultimately EDS and microprobe, FTIR, and XRF – in order to be able to fully understand the formation of a sediment at the microscale.

The above shows how important it is to study intact samples along with bulk samples and how crucial it is to have flawless contextual correlation among the samples. For many years Neolithic Mediterranean cave sediments were simply associated with stabling of domestic animals, mainly sheep and goats, because of the presumed mineral remains of dung (composed of calcite dung spherulites and phytoliths) that were commonly found in bulk samples. When these cave sediments were studied systematically through soil micromorphology (as well as through EDS and macrofossil analysis of plant remains present in thin sections), a more sophisticated understanding of cave use was realized. For example, domestic space – and periods when domestic occupation dominated – was clearly differentiated from stabling areas and episodes. Moreover, microstratigraphic analysis revealed that stabling produced repeated sediment sequences from seasonal overwintering of stock and that animals were fed on a leaf hay fodder (e.g., *Quercus ilex*), which produces very few phytoliths (Macphail et al., 1997); in contrast to domestic use sediments these stabling deposits were



Microstratigraphy, Figure 8 Microprobe map of M309B (Figure 7), showing distribution of Ca (chalk, calcite ashes, etc.), Fe (e.g., iron-stained organic matter), and P (phosphate-stained organic matter – typical of stabling waste). Here, domestic constructional debris and ash residues were dumped over organic stabling debris. Ashes appear associated with lead concentrations (0.09 % Pb). Scale =5 mm.

then also burned in situ. Faunal remains supported the identification of overwintering of stock in sediments showing these cycles of stabling.

When human activities are added to the mix, the interpretation of microstratigraphy becomes increasingly difficult. This has been mitigated by the analysis of microfacies types produced during experiments and ethnoarchaeological analogues. Examples include complementing micromorphology with image analysis to study a Bedouin camp and adding pollen, bulk, and microchemistry to microfacies analysis of domestic and stabling floor investigations at the experimental Iron Age farm at Butser, Hampshire, UK (Goldberg and Whitbread, 1993; Macphail et al., 2004). In the latter case, in situ stabling deposits and intact dumped stabling refuse were shown to have typical a multidisciplinary signature. This yardstick has permitted the identification of well-preserved byre (cowshed) waste dumps, as, for example, in the fourteenth-century environs of Winchester Cathedral, by the River Itchen (Figures 7 and 8). The stabling waste is composed of microlaminated long plant stems of grasses and cereals that are part cemented with phosphate, as typical of stable floor crusts; the pollen analysis revealed a typical fodder plant composition. This layer is overlain by chalky floor construction dumps and ash residues, which are themselves enriched in lead (Pb).

Conclusions

It can be seen that by employing the geological concept of microstratigraphy, geoarchaeologists can greatly improve the characterization of stratigraphy on archaeological sites. Moreover, microstratigraphy is best observed and studied in thin section, which then can be further analyzed using small bulk samples for chemistry, magnetic susceptibility, and microfossils; macrofossil, EDS, FTIR, and reflected light (char) analyses can be carried out directly on the thin section in some cases. Overall, consensus interpretations of both vertical sequences and lateral differences in use of space can all be recognized and interpreted.

Bibliography

Artioli, G., 2010. *Scientific Methods and Cultural Heritage*. New York: Oxford University Press.

Barba, L., 2007. Chemical residues in lime-plastered archaeological floors. *Geoarchaeology*, **22**, 439–452.

Courty, M. A., 2001. Microfacies analysis assisting archaeological stratigraphy. In Goldberg, P., Holliday, V. T., and Ferring, C. R. (eds.), *Earth Sciences and Archaeology*. New York: Kluwer, pp. 205–239.

Courty, M.-A., Goldberg, P., and Macphail, R. I., 1989. *Soils and Micromorphology in Archaeology*. Cambridge: Cambridge University Press.

Courty, M. A., Goldberg, P., and Macphail, R. I., 1994. *Ancient People – Life Styles and Cultural Patterns, Transactions of the 15th World Congress of Soil Science, International Society of Soil Science, Mexico*. Acapulco: International Society of Soil Science, Vol. 6a, pp. 250–269.

Crowther, J., 2003. Potential magnetic susceptibility and fractional conversion studies of archaeological soils and sediments. *Archaeometry*, **45**, 685–701.

Encyclopædia Britannica Online, s. v. "sedimentary facies". Accessed February 22, 2012. http://www.britannica.com/EBchecked/topic/532223/sedimentary-facies.

Encyclopædia Britannica Online, s. v. "stratigraphy". Accessed February 22, 2012. http://www.britannica.com/EBchecked/topic/568372/stratigraphy.

Flügel, E., 2004. *Microfacies of Carbonate Rocks*. Berlin: Springer Verlag. 976 p.

Gé, T., Courty, M. A., Matthews, W., and Wattez, J., 1993. Sedimentary formation processes of occupation surfaces. In Goldberg, P., Nash, D. T., and Petraglia, M. D. (eds.), *Formation Processes in Archaeological Contexts*. Madison, WI: Prehistory Press. Volume Monographs in World Archaeology No. 17, pp. 149–163.

Gilbertson, D. D., 1995. Studies of lithostratigraphy and lithofacies: a selective review of research developments in the last decade and their applications to geoarchaeology. In Barham, A. J., and Macphail, R. I. (eds.), *Archaeological Sediments and Soils: Analysis, Interpretation and Management*. London: Institute of Archaeology, pp. 99–145.

Goldberg, P., 1975. Sediment peels from prehistoric sites. *Journal of Field Archaeology*, **1**, 323–328.

Goldberg, P., and Berna, F., 2010. Micromorphology and context. *Quaternary International*, **214**, 56–62.

Goldberg, P., and Macphail, R., 2003. Strategies and techniques in collecting micromorphology samples. *Geoarchaeology*, **18**, 571–578.

Goldberg, P., and Whitbread, I., 1993. Micromorphological study of a Bedouin tent floor. In Goldberg, P., Nash, D. T., and Petraglia, M. D. (eds.), *Formation Processes in Archaeological Context*.

Madison: Prehistory Press. Volume Monographs in World Archaeology No. 17, pp. 165–188.
Laville, H., Rigaud, J.-P., and Sackett, J., 1980. *Rock Shelters of the Perigord*. New York: Academic Press.
Macphail, R. I., Courty, M. A., Hather, J., and Wattez, J., 1997. The soil micromorphological evidence of domestic occupation and stabling activities. In Maggi, R. (ed.), *Arene Candide: A Functional and Environmental Assessment of the Holocene Sequence (Excavations Bernabò Brea-Cardini 1940–1950)*. Roma: Memorie dell'Istituto Italiano di Paleontologia Umana, pp. 53–88.
Macphail, R. I., Cruise, G. M., Allen, M. J., Linderholm, J., and Reynolds, P., 2004. Archaeological soil and pollen analysis of experimental floor deposits; with special reference to Butser Ancient Farm, Hampshire, UK. *Journal of Archaeological Science*, **31**, 175–191.
Parnell, J. J., and Terry, R. E., 2002. Soil chemical analysis applied as an interpretive tool for ancient human activities in Piedras Negras, Guatemala. *Journal of Archaeological Science*, **29**, 379–404.
Rosen, A. M., 1993. Microartifacts as a reflection of cultural factors in site formation. In Goldberg, P., Nash, D. T., and Petraglia, M. D. (eds.), *Formation Processes in Archaeological Context*. Madison: Prehistory Press, pp. 141–148.
Sherwood, S. C., Simek, J. F., and Polhemus, R. R., 1995. Artifact size and spatial process; macro- and microartifacts in a Mississippian house. *Geoarchaeology*, **10**, 429–455.
Texier, J.-P., Kervazo, B., Lenoble, A., and Nespoulet, R., 2004. Sédimentogenèse des sites préhistoriques du Périgord [excursion des] 23–24 avril 2004. [Association des sédimentologistes français, [Paris].
Weiner, S., 2010. *Microarchaeology*. Cambridge: Cambridge University Press.

Cross-references

Cave Settings
Fourier Transform Infrared Spectroscopy (FTIR)
Rockshelter Settings
Scanning Electron Microscopy (SEM)
Site Formation Processes
Soil Micromorphology
Stratigraphy
X-ray Diffraction (XRD)

MINNESOTA MESSENIA EXPEDITION (MME)

George Rip Rapp
Department of Geological Sciences, University of Minnesota, Duluth, MN, USA

The Minnesota Messenia Expedition (MME) was the first major multidisciplinary archaeological expedition in Greece. Its focus was the Bronze Age and involved surface survey, large-scale excavation, with many integrated studies focusing on paleoenvironmental reconstruction, archaeological science, cultural history, and social anthropology (McDonald and Rapp, 1972; Rapp and Aschenbrenner, 1978; McDonald et al., 1983; McDonald and Wilkie, 1992). Although this project was not organized formally until 1962, survey work began in 1958 after Carl Blegen had suggested to William McDonald the critical need for such a survey. Regular surface survey initially was conducted by McDonald and Richard Hope Simpson. During the 1960s, McDonald realized the need for associated scientific studies and engaged H. E. Wright, Jr. (paleoecology), William Loy (geography), Jesse Fant (civil engineering), and others to conduct them. This culminated in 1966 with the addition of geoarchaeologist George (Rip) Rapp being named associate director. He expanded the scope of the scientific investigations into other specialties, such as archaeometallurgy and coastal change, and assisted McDonald in securing the permit to excavate the site of Nichoria.

Based on the years of archaeological survey, which located hundreds of sites, seven sites were identified as most worthy for excavation. The "lower town" of the Pylos Palace was the highest priority, with Nichoria second. Having excavated the palace, Blegen controlled the permit for the palace area. He suggested that another site be selected, so Nichoria was picked and the permit was secured. With McDonald as director and Rapp as associate director, excavations began in 1969; they continued through 1975. Based on the Linear B tablets found at the palace, it was believed that there was a subsidiary capital of a "further province" in the Pylean Kingdom. Nichoria was considered to be the best candidate for this. It was located on a ridge with a commanding view of both land and sea.

Excavation began in 1969 with a so-called trial trench season. Subsequent years of excavation exposed well-preserved deposits ranging from the Middle and Late Helladic (Bronze Age), through the Dark Age (Early Iron Age) to the Byzantine (Medieval). As in the survey, the excavation staff was composed of scholars representing a wide range of disciplines. To facilitate their studies, a large "dig house" was constructed with specialized areas and facilities (see Rapp and Aschenbrenner, 1978: Plates 1–2 through 1–16). Space and equipment was available for ethnobotany, sedimentology, petrography, osteology, color and black and white film processing, as well as the standard ceramic and lithic studies. For the recovery of small-scale remains, a screening and gravity concentration unit was constructed near the excavation house.

MME's geoarchaeological studies were published in McDonald and Rapp (1972) and in Rapp and Aschenbrenner (1978). The relevant chapters in the 1972 volume were The Physical Setting, Soil Studies, Metallurgical and Geochemical Studies, and Geophysical Exploration. The geoarchaeological chapters in the 1978 volume were Introduction, The Holocene Environmental History of the Nichoria Region, The Physiographic Setting, Soil Formation, Lithological Studies, and Archaeological Geology of the Site.

MME is likely to be remembered for its pioneering role in multidisciplinary survey and excavation. It should be noted that the MME survey was a reconnaissance survey, not an intensive survey. Many years later part of the region covered by MME received the needed intensive survey, led by Jack Davis (Davis and Alcock, 1998).

Bibliography

Davis, J. L., and Alcock, S. E. (eds.), 1998. *Sandy Pylos: An Archaeological History from Nestor to Navarino*. Austin: University of Texas Press.
McDonald, W. A., and Rapp, G. R. (eds.), 1972. *The Minnesota Messenia Expedition: Reconstructing a Bronze Age Regional Environment*. Minneapolis: University of Minnesota Press.
McDonald, W. A., and Wilkie, N. C. (eds.), 1992. *Excavations at Nichoria in Southwest Greece. Vol. II: The Bronze Age Occupation*. Minneapolis: University of Minnesota Press.
McDonald, W. A., Coulson, W. D. E., and Rosser, J. (eds.), 1983. *Excavations at Nichoria in Southwest Greece. Vol. III: Dark Age and Byzantine Occupation*. Minneapolis: University of Minnesota Press.
Rapp, G. R., and Aschenbrenner, S. E. (eds.), 1978. *Excavations at Nichoria in Southwest Greece. Vol. I: Site, Environs, and Techniques*. Minneapolis: University of Minnesota Press.

Cross-references

Field Survey

MONTE CIRCEO CAVES

Francesco G. Fedele
Formerly University of Naples 'Federico II', Naples, Torino, Italy

Definition

Cape Circeo is an isolated point of high relief, 541 m in elevation, presently configured as a cape on the Latium coast in central Italy (41°14′ N, 13°05′ E). It was a landmark to early Greek sailors and named after Circe, the mythical enchantress thought to live in its woods (Homer's *Odyssey*, Book 10).

Archaeological study of the caves in the limestone units of Monte Circeo began in 1939 when a Neanderthal skull, reportedly within a circle of stones, was found inside a newly discovered cave exposed by construction work. The cave, later named Grotta Guattari (20 m asl), had been sealed by rock debris at about 50 ka and contained a preserved floor or "archaeosurface" with underlying stratification. Contrary to past interpretations of the bone remains from the floor as evidence for Paleolithic ritual behavior, both taphonomic and zooarchaeological studies reveal that the aggregates, hominin cranial fossils included, are the product of denning by spotted hyenas (Stiner, 1991; White and Toth, 1991; Bietti and Manzi, 1992). In fact, large carnivores, including cave hyena (*Hyaena spelaea*) and leopard (*Panthera pardus*), appear to have used the Circeo cavities regularly as dens during the last glacial period.

At Guattari, the strata below the cave surface reproduce the general stratigraphy of Monte Circeo's sea level cave belt, which reveals from the base upward: (1) Marine Isotope Stage (MIS) 5 aggradational beach deposits with the marine gastropod *Strombus bubonius* (ca. 100–75 ka), (2) continental sands and concretions containing "Pontinian" Mousterian assemblages made from beach pebbles and associated faunas (early last glacial), and (3) partly indurated, thermoclastic cave sediments containing Mousterian industry and culturally derived faunas, often suggesting opportunistic procurement of red deer and aurochs. Contemporary, mid-last glacial breccia formation occurs in the outer part of several caves.

During the glacial low sea stand, Monte Circeo dominated on three sides an extensive coastal plain. Other important archaeological caves include Grotta Breuil and Grotta del Fossellone, both presently at sea level. Breuil provided a well-studied instance of later Mousterian adaptations, land-use strategies, and cave space organization (Spinapolice, 2006). At Fossellone, an impressive 14-m-thick fill spanning the whole Late Pleistocene contains Mousterian and Upper Paleolithic occupations, the latter amounting to tens of Aurignacian and Epigravettian levels. From the Aurignacian layers, two pendants made from rare steatite and imitating red deer canines are known (Mussi, 1988–89). Both caves have produced several more Neanderthal remains (Alciati et al., 2005).

Francesco G. Fedele retired

Bibliography

Alciati, G., Pesce Delfino, V., and Vacca, E. (eds.), 2005. *Catalogue of Italian Fossil Human Remains from the Palaeolithic to the Mesolithic. Journal of Anthropological Sciences*, supplement to volume 83 for 2005. Roma: Istituto Italiano di Antropologia, Università La Sapienza.
Bietti, A., and Manzi, G. (eds.), 1992. *The Fossil Man of Monte Circeo: Fifty Years of Studies on the Neandertals in Latium*. Quaternaria Nova 1. Rome: Istituto Italiano di Paleontologia Umana.
Mussi, M., 1988–89. L'uso della steatite nel Paleolitico Superiore italiano. *Origini: Preistoria e Protostoria delle Civiltà Antiche*, **14**: 189–205.
Spinapolice, E., 2006. L'uso dello spazio a Grotta Breuil: Risultati preliminari dall'analisi degli strati inferiori (6, 7 e 8). *Rivista di Scienze Preistoriche*, **56**, 1–14.
Stiner, M. C., 1991. The faunal remains from Grotta Guattari: a taphonomic perspective. *Current Anthropology*, **32**(2), 103–117.
White, T. D. and Toth, N., 1991. The question of ritual cannibalism at Grotta Guattari. *Current Anthropology*, **32**(2), 118–138.

MONTE VERDE

Tom D. Dillehay
Department of Anthropology, Vanderbilt University, Nashville, TN, USA

Definition

Monte Verde is located in south-central Chile (Dillehay, 1997). The site is an open-air campsite on the banks of a small stream, surrounded by sandy knolls, small bogs, and damp forests that have been there since 15,000 bp.

The bog later developed in the stream basin, covering the abandoned site under a layer of peat. Because the lack of oxygen in the bog inhibited bacterial decay, and because the constant saturation prevented drying for thousands of years, various types of organic materials that normally disappear from archaeological sites through decay processes have been preserved. An interdisciplinary research team of more than 60 scientists studied the remains excavated from two areas at the site, called Monte Verde I and Monte Verde II.

Monte Verde II exhibits the remains of a long tentlike structure made of wood and animal hides. Several pieces of cordage and string made of reed wrapped around wooden posts and stakes, recovered among the architectural remains, show that the people planned a lengthy stay. The tent's dirt floor was embedded with hundreds of microscopic flecks of hide tissue, suggesting that it was covered with animal skins. On the floor of the tent were brazier pits lined with clay and surrounded by stone tools and the remains of edible seeds, nuts, and berries. Outside the tent were two large communal hearths, a store of firewood, wooden mortars with their grinding stones, and three human footprints near one of the large hearths. All these remains indicate tasks, primarily food preparation and consumption, tool production and maintenance, and the construction of shelters.

A second structure was wishbone-shaped in ground plan and made of wooden uprights set into a foundation of sand and gravel. Parts of gomphothere (*Cuvieronius* sp.) and paleo-llama (*Paleollama llama*) carcasses were butchered, hides were prepared, and stone and wood tools were manufactured in and around the structure. Eighteen probable medicinal plant species were found inside the structure as well. The remains of a wide variety of local and nonlocal edible plants also were recovered from the hearths, living floors, and small pits. The presence of exotic foods, including seaweed, and other items at the site shows that distant coastal habitats provided important resources to the Monte Verde economy. Three different stone tool technologies also exist at the site, including bifacial tools, unifacial implements and waste debris, and grinding stones.

The distinct living structures, features, and concentrations of specific materials at the site suggest that occupation was continuous and that portions of the site were used more intensively than others. Different kinds of artifacts give evidence of a wide variety of activities. A long sequence of radiocarbon dates on different materials from the site place the Monte Verde II occupation at about 12,500 BP.

Buried in a different area of Monte Verde is a possibly earlier occupation, Monte Verde I, with twenty-six stone tools and three burned clay features. Radiocarbon dates placed this possible occupation around 33,000 years ago.

Bibliography

Dillehay, T. D., 1997. *Monte Verde: A Late Pleistocene Settlement in Chile*. Washington, DC: Smithsonian Institution Press. The Archaeological Context and Interpretation, Vol. 2.

MOUNT CARMEL

Claudio Vita-Finzi
Natural History Museum, London, NW, UK

Definition

In archaeological contexts, the name Mount Carmel usually denotes four caves 20 km south of Haifa on Wadi el Mughara – es-Skhul, et-Tabun, el-Wad, and el-Jamal – although the area is now known to include at least 283 prehistoric sites (Olami, 1984).

Background

The caves were first excavated by British prehistorian Dorothy Garrod and her colleagues in 1929–1934 (Garrod and Bate, 1937). More recent excavations have been carried out at Tabun by A. J. Jelinek in 1969–1971 and then by A. Ronen from 1975 and at Wad by F. R. Valla and O. Bar-Yosef in 1980–1981 and by M. Weinstein-Evron since 1988. In 2012, Mount Carmel was named a UNESCO World Heritage Site.

The caves are about 45 m above sea level and a little over 3 km from the present Mediterranean coast from which they are separated by a range of fossil calcareous sand dunes (*kurkar*), with intervening sediments representing former swamps some of which were drained by channels cut through the *kurkar* in Roman times. Drilling on the coastal plain has yielded evidence of a number of marine transgressions and regressions dating from the Pleistocene.

The stratigraphy of the four caves as delineated by Garrod and Bate (1937) was based mainly on artifact typology, and it was linked on that basis to the sequence of Pleistocene pluvials identified in the Jordan Valley (Picard, 1937) and the raised shorelines of Lebanon and other parts of the Mediterranean and thus to the fourfold Alpine glacial sequence then in favor (Zeuner, 1945). Components of the stratigraphy, sedimentology, and faunal remains of the caves later received attention (e.g., Coles and Higgs, 1969; Jelinek et al., 1973; Tsatskin 2000), and ESR, TL, $^{10}Be/^{26}Al$, and U/Th techniques, especially in the context of paleoanthropology, have shown that most of the radiocarbon dates obtained in the 1960s represent minimum ages. For example, it is now known that the Tabun sequence spans over 400,000 years rather than 50,000 (Grün and Stringer, 2000; Mercier and Valladas, 2003; Rink et al., 2003).

Es-Skhul

Four major stratigraphic units are generally recognized within the cave. Starting from the bottom, layer C overlies sterile sand and contains abraded artifacts cemented into a breccia; layers B2 and B1 contain a Levalloiso-Mousterian lithic industry with some resemblance to material in Tabun; layer A contains a mixture of Natufian, late Paleolithic, and Levalloiso-Mousterian material and pottery from later periods. Marine mollusks from pre-Natufian levels include the saltwater clam *Acanthocardia deshayesi* (Payraudeau, 1826), the cockle *Laevicardium crassum* (Gmelin, 1791), the scallop *Pecten jacobaeus* (L), and the sea snail *Nassarius gibbosulus* (Linnaeus, 1758), the last from layer B and including specimens artificially perforated and presumably brought in by humans. Layer B also yielded remains of a bovid, pig, rhinoceros, and hippopotamus, but their ecological significance is disputed (Coles and Higgs, 1969). Abrasion of the layer C material was ascribed to spring action within the cave (Garrod and Bate, 1937).

At least ten individuals – seven adults and three juveniles – were uncovered, some of whom appear to have been intentionally buried. Bearing a close similarity to hominins recovered from Qafzeh Cave in the Galilee to the north, they have been dated by mass-spectrometric U-series, TL, and ESR analyses and appear to have lived at some time between 100 and 135 ka (Grün et al., 2005).

Et-Tabun

At Tabun Cave, the basal layer (G) contains a Tayacian lithic industry; layer F yields final Acheulean; layers Ed, Ec, and Ea Yabrudian, layer Eb Amudian; layers D, C, and B Levalloiso-Mousterian; and layer A Bronze Age to recent. The mammalian fauna of layer F consisted largely of extinct species (McCown and Keith, 1939), but it included a high percentage of fallow deer (*Dama mesopotamica*). Hippopotamus and rhinoceros persist in layers C and D, together with substantial gazelle content, but high values of *Dama* return in layer B. The relative proportions of deer and gazelle once inspired a graph reflecting the alternation of dry/wet conditions over time, but the scheme is now considered too simplistic. Layers E and F are dominated by windblown material (Jelinek et al., 1973). Layer F contains the marine dwarf oyster *Ostreola stentina*, given as *Ostrea crenulifera* (Sowerby, 1871) in Garrod and Bate (1937).

Tabun layer B has yielded an archaic *H. sapiens* female skeleton (named Tabun C1 but probably from layer B) and a separate mandible. U-series and ESR dating give C1 a combined age of about 143 ± 37 ka (Grün and Stringer, 2000), and a tooth from layer Ed has given a combined ESR/U-series age of 387 ± 40 ka (Rink et al., 2003). A TL determination on a burnt flint from Tabun G gave an age of ~415 ka (Mercier et al., 2000).

El-Wad

The basal layer (G) at el-Wad contains Mousterian and Emiran ("Advanced Paleolithic") material; layers F to C contain Advanced Paleolithic, with the artifacts in C equated with the Atlitian; layers B1 and B2 contain Natufian and have yielded more than 100 burials dated to 15–13 cal ka (Weinstein-Evron et al., 2012). Charcoal from the Natufian levels, including *Tamarix* sp., *Quercus calliprinos* Webb, *Q. ithaburensis* Decne, and *Cupressus sempervirens* L., reflect a Mediterranean climate similar to that of the present (Lev-Yadun and Weinstein-Evron, 1994).

Part of layer F, forming a sublayer some 10 cm thick in the cave, contains abraded and heavily rolled Levalloiso-Mousterian artifacts free from matrix. The underlying deposit G here is 4.3 m thick and consists of hardened gray grit lacking in artifacts or faunal material (Garrod and Bate, 1937). The elevation of this section corresponds with the upper part of layer C in Skhul, which, as noted above, also contained abraded artifacts. The abrasion has been ascribed to spring action in both Wad and Skhul.

El Jamal

Long considered to be almost empty, Jamal Cave has yielded Acheulo-Yabrudian material, together with two Levallois-style flakes, embedded within cemented sediments with a maximum thickness of 1.5 m that betray redeposition (Weinstein-Evron and Tsatskin, 1994). The presence of Levallois material in the Upper Acheulean of the Levant is considered commonplace. A sample of flowstone overlying the archaeological layer gave a $^{230}Th/^{234}U$ age of 220–223 ka (Zaidner et al., 2005). The absence of later industries contrasts with the long record of the other Mount Carmel caves.

The abrasion on pebbles and artifacts in layer F and G of Wad Cave and in layer C of Skhul Cave that was first ascribed to spring action is consistent with shoreline deposition about 120,000 years ago, when sea level was 5–6 m above its present datum. This would therefore indicate subsequent uplift by 40 m of Mount Carmel, which is bordered on the west by fossil beaches up to 125 m high and on the east by the active Carmel fault (Vita-Finzi and Stringer, 2007; but see Galili et al., 2007; Zvieli et al., 2009).

The faunal remains and artifact assemblages in the caves point to a range of economic strategies, including the seasonal exploitation by hunters of deer and other herds at times of low sea level (Vita-Finzi and Higgs, 1970; Marín-Arroyo, 2013). Local environmental history thus overrides the coarser narrative of alternating glacial and interglacial times derived from the climatic record of glaciated areas in high altitudes and latitudes. What is more, the caves lie "on a great highway of migration" between Africa and Asia (McCown and Keith, 1939, 226) so that seemingly parochial changes in topography and resources must at times have acted as barriers or bridges between those two realms.

Bibliography

Coles, J. M., and Higgs, E. S., 1969. *The Archaeology of Early Man*. London: Faber and Faber.

Galili, E., Zviely, D., Ronen, A., and Mienis, H. K., 2007. Beach deposits of MIS 5e high sea stand as indicators for tectonic stability of the Carmel coastal plain. *Quaternary Science Reviews*, **26**(19–21), 2544–2557.

Garrod, D. A. E., and Bate, D. M. A., 1937. *The Stone Age of Mount Carmel*. Oxford: Clarendon Press, Vol. I.

Grün, R., and Stringer, C. B., 2000. Tabun revisited: revised ESR chronology and new ESR and U-series analyses of dental material from Tabun C1. *Journal of Human Evolution*, **39**(6), 601–612.

Grün, R., Stringer, C., McDermott, F., Nathan, R., Porat, N., Robertson, S., Taylor, L., Mortimer, G., Eggins, S., and McCulloch, M., 2005. U-series and ESR analyses of bones and teeth relating to the human burials from Skhul. *Journal of Human Evolution*, **49**(3), 316–334.

Jelinek, A. J., Farrand, W. R., Haas, G., Horowitz, A., and Goldberg, P., 1973. New excavations at the Tabun Cave, Mount Carmel, Israel, 1967–1972: a preliminary report. *Paléorient*, **1** (1–2), 151–183.

Lev-Yadun, S., and Weinstein-Evron, M., 1994. Late Epipalaeolithic wood remains from el-Wad Cave, Mount Carmel. Israel. *New Phytologist*, **127**(2), 391–396.

Marín-Arroyo, A. B., 2013. Palaeolithic human subsistence in Mount Carmel (Israel). A taphonomic assessment of Middle and Early Upper Palaeolithic faunal remains from Tabun, Skhul and el-Wad. *International Journal of Osteoarchaeology*, **23**(3), 254–273.

McCown, T. D., and Keith, A., 1939. *The Fossil Human Remains from the Levalloiso-Mousterian. The Stone Age of Mount Carmel*. Oxford: Clarendon Press, Vol. II.

Mercier, N., and Valladas, H., 2003. Reassessment of TL age estimates of burnt flints from the Paleolithic site of Tabun Cave, Israel. *Journal of Human Evolution*, **45**(5), 401–409.

Mercier, N., Valladas, H., Froget, L., Joron, J.-L., and Ronen, A., 2000. Datation par thermoluminescence de la base du gisement paléolithique de Tabun (mont Carmel, Israël); TL Dating of the lowest Paleolithic deposits of the Tabun Cave (Mt. Carmel, Israel). Comptes Rendus de l'Académie des Sciences - Series IIA - Earth and Planetary Science, **330**(10), 731–738.

Olami, Y., 1984. *Prehistoric Carmel*. Jerusalem: Israel Exploration Society.

Picard, L., 1937. Inferences on the problem of the Pleistocene climate of Palestine and Syria drawn from flora, fauna and stratigraphy. *Proceedings of the Prehistoric Society, N. S.* **3**(1–2), 58–70.

Rink, W., Bartoll, J., Goldberg, P., and Ronen, A., 2003. ESR dating of archaeologically relevant authigenic terrestrial apatite veins from Tabun Cave, Israel. *Journal of Archaeological Science*, **30**(9), 1127–1138.

Tsatskin, A., 2000. Acheulo-Yabrudian sediments of Tabun: a view from the microscope. In Ronen, A., and Weinstein-Evron, M. (eds.), *Toward Modern Humans: The Yabrudian and Micoquian, 400-50 k-years Ago: Proceedings of a Congress Held at the University of Haifa, November 3–9, 1996*. Oxford: Archaeopress. British Archaeological Reports, International Series, 850, pp. 133–142.

Vita-Finzi, C., and Higgs, E. S., 1970. Prehistoric economy in the Mount Carmel area of Palestine: site catchment analysis. *Proceedings of the Prehistoric Society*, **36**, 1–42.

Vita-Finzi, C., and Stringer, C., 2007. The setting of the Mt. Carmel caves reassessed. *Quaternary Science Reviews*, **26**(3–4), 436–440.

Weinstein-Evron, M., and Tsatskin, A., 1994. The Jamal cave is not empty: recent discoveries in the Mount Carmel caves, Israel. *Paléorient*, **20**(2), 119–128.

Weinstein-Evron, M., Yeshurun, R., Kaufman, D., Eckmeier, E., and Boaretto, E., 2012. New 14C dates for the Early Natufian of el-Wad terrace, Mount Carmel, Israel. *Radiocarbon*, **54** (3–4), 813–822.

Zaidner, Y., Druck, D., Nadler, M., and Weinstein-Evron, M., 2005. The Acheulo-Yabrudian of Jamal Cave, Mount Carmel, Israel. *Mitekufat Haeven: Journal of the Israel Prehistoric Society*, **35**, 93–115.

Zeuner, F. E., 1945. *The Pleistocene Period: Its Climate, Chronology, and Faunal Successions*. London: Ray Society.

Zvieli, D., Galili, E., Ronen, A., Salamon, A., and Ben-Avraham, Z., 2009. Reevaluating the tectonic uplift of western Mount Carmel, Israel, since the middle Pleistocene. *Quaternary Research*, **71**(2), 239–245.

Cross-references

Cave Settings
Electron Spin Resonance (ESR) in Archaeological Context
U-Series Dating

N

NEUTRON ACTIVATION ANALYSIS

Ronald L. Bishop
Department of Anthropology, National Museum of Natural History, Smithsonian Institution, Washington, DC, USA

Synonyms

INAA (Instrumental Neutron Activation Analysis); NAA

Definition

Neutron activation analysis is a highly sensitive and precise technique of elemental analysis using nuclear properties

Neutron activation analysis

Neutron activation analysis (NAA) is a well-established chemical analytical technique for the accurate identification and highly precise quantification of elemental constituents in a wide variety of matrices (de Soete and Hoste, 1972; Harbottle, 1976; Neff, 2000). It is based on properties of samples that involve induced radioactivity within the nucleus of atoms rather than the chemical and physical form in which the samples exist. This technique requires the exposure of the sample to a source of neutrons, most frequently in a nuclear reactor, and it has been widely applied in studies of environmental, biological, geological, and archaeological specimens. The method most frequently used takes an instrumental approach (INAA) that entails no postirradiation radiochemical separations. INAA is known for its great sensitivity in the detection and quantification of elemental constituents, including those present in trace and ultra trace concentrations, and its capability for simultaneous multielemental determinations that are largely free of matrix effects or interferences. Because neutrons penetrate most materials in a uniform manner, analysis can be carried out on small solid samples, thereby greatly reducing the sample preparation time required by most other instrumental analytical techniques and, with moderate laboratory care, lowering the risks of contamination. Over more than half century during which INAA has been used the generation of reliable results has made it the standard against which newer techniques of multielement analysis are compared.

A nuclide is an atom characterized by the number of protons and neutrons, *i.e., an atom with a specific nuclear composition*. The number of protons determines the *atomic number* of the atom, while the sum of the protons and neutrons determines the *mass number*. The nuclei of atoms of the same chemical element have the same atomic number, but need not have the same mass number. When the nucleus of an atom has the same atomic number but differs in the number of neutrons, it is said to be an *isotope* of that atom. Many, but not all, naturally occurring *elements* are mixtures of isotopes of varying abundance. Some combinations of protons and neutrons are unstable, *or radioactive, and these radionuclides* decay by various means to stable combinations at rates, *or half-lives, that are* specific to the *radionuclide*.

When a neutron is absorbed by a target nucleus, several physical effects can take place, but the primary reaction of interest involves the "capture" of a neutron by a nucleus. This process forms an intermediate or compound nucleus that is in a highly energetic state. De-excitation of the nucleus occurs in different ways, including the release of particles (alpha or beta) and gamma rays of discrete energies. Gamma rays are photons of electromagnetic radiation, similar to light but much more energetic. The release of gamma rays by an excited nucleus may occur as the nucleus captures a neutron, and these emissions are termed "prompt" gamma rays. With the appropriate instrumentation, the prompt gamma emissions may be detected, sorted as to energy, and counted. This is referred

A.S. Gilbert (ed.), *Encyclopedia of Geoarchaeology*, DOI 10.1007/978-1-4020-4409-0,

to as prompt gamma neutron activation analysis or PGNAA (Lindstrom and Yonezawa, 1995). More typically, however, INAA utilizes delayed gamma rays (DGNAA) that are emitted as the radionuclide decays according to the half-life of the radioactive isotopes that have been formed. The important properties of these gamma ray emissions lie in their having energies and intensities that are characteristic of specific isotopes, which lend themselves to the identification and quantification of a sample's elemental constituents.

This process can be illustrated using the element cobalt. All cobalt occurs in nature as a single stable isotope with an atomic number of 27 and a mass number of 59 (i.e., 27 protons and 32 neutrons in the nucleus), and the element is represented symbolically as Co-59. Under conditions of neutron bombardment, the nucleus can capture an incident neutron forming the radioactive isotope, cobalt-60. The radioisotope decays with a half-life of 5.27 years, forming the stable isotope Ni-60 through the emission of a beta particle and two energetic gamma rays of 1.17 MeV and 1.33 MeV. Like that of Co-60, the decay schemes for most radionuclides elements are well determined, as are the energies of gamma emissions that are characteristic of isotopes of that element. Since the gamma emissions of the radioactive isotopes of all elements in a multi-element sample are going on simultaneously, a spectrum of energies and intensities is created. When the irradiated sample is placed in front of a gamma ray detector, (usually a high purity or lithium-drifted germanium detector), and its associated electronics, a percentage of the incident gamma ray photons emitted from decaying sample atoms interacts with the detector material to produce a photoelectric discharge of electrons proportional in energy to the incident gamma ray. These reactions are sorted according to energy and quantified to constitute an isotopic pattern for the analyzed sample.

Some commonly determined elements have isotopic half-lives (the time it takes for one-half of the radioactivity to decay) of only a few minutes (Al, Ti, V), others a few hours (e.g., Mn, Na, K, La), days (e.g., Ca, Sc, Cr, Fe, Zn, As, Br, Rb, Sr, Zr, Sb, Ba, Ce, Nd, Sm, Tb, Yb, Lu, Hf, Ta, Th, U), or years (e.g., Co, Cs, Eu). The detection and counting of emissions are carried out at specific intervals following the end of irradiation(s) in order to measure isotopes with half-lives of different lengths. Which isotopes are detected depends upon several factors including (1) the abundance of the target nuclei, (2) the likelihood that an incident neutron will react with a target nucleus (thermal neutron cross section), (3) the density and duration of the neutron bombardment, (4) size of the sample being irradiated, (5) the decay period, and (6) the specifics of the counting environment. The high sensitivity of INAA for detecting elements occurring at very low concentrations permits some 70 elements to be identified. However, using routine procedures of delayed gamma spectroscopy, it is more likely that 30-40 elemental concentrations can be determined. If this is supplemented through the use of PGNAA, another 5-6 elements (Al, Ca, Cl, Dy, Ti and V) can be added to the list (Glascock, 1994). The elements tend to be spread across the periodic table and include alkali metals, the alkaline earths, transition elements, halides, and the lanthanide and actinide series. This means that the resulting data can be searched for information pertaining not only to elemental abundance but also for patterns of elemental association and chemical behavior (e.g., fractionation among the rare earth elements).

At the end of sample irradiation, the activity of the radioisotopes is proportional to the number of target nuclei in the sample. Quantification of elemental abundance can be carried out by comparing the unknown sample to a standard reference material of known elemental concentrations that has been treated under the same irradiation conditions. Appropriate corrections must be made for differences in weight, radioactivity, and time elapsed since the end of irradiation. Comparator standards include the certified reference materials available from the National Institute of Standards and Technology (e.g., Coal Fly Ash 1633c, Brick Clay 679, Marine Sediment 2702), and may be supplemented by a "check standard" such as the commercially available air-floated, Redart, 200-mesh Ohio Red Clay (Djingova et al., 1990). The use of a comparator standard does introduce additional error, however, as the abundances in the reference material are certified to varying degrees of certainty. Alternatively, the data can be quantified through a K_0 method using gold as the single comparator (De Corte, 1987; Kennedy and St-Pierre, 1999), but this requires detailed knowledge of the neutron spectrum and flux.

Not all elemental concentrations can be determined by NAA. Some elements do not form radioactive nuclei, some may have severe spectral interferences, and some or cannot be reliably determined without expending excessive analytical time that would reduce the number of samples that could be analyzed. Each determined elemental concentration has some magnitude of error associated it, and these errors may arise from analytical factors, such as counting statistics, geometry, gamma peak shape and location, interferences and peak integration, and comparator reference standards, among others. Despite these sources of variation, many of which can be reduced to an acceptable level, many elemental concentrations can be determined with high analytical precision (1-2 % error), others with 5-10 % uncertainties and a few with greater uncertainties (e.g., As, Ba, Nd, Sr, and Zr).

Archaeological use of neutron activation data, which is really just a description of variably quantified elemental constituents, requires more than just careful analysis: it requires attention to sample design and reasoned data analysis (Harbottle 1976; Bishop et al., 1982; Neff 2000; Bishop, 2003). No matter how specifically the initial archaeological question is focused, most applications of

INAA in archaeology are regional in scope. They represent attempts to understand chemical variation in archaeological materials in a manner that permits social, economic, or political interpretations pertaining to the acquisition, use, and discard of cultural material, and such a perspective can be obtained most effectively by broad spatial or temporal sample comparisons. Most situations are complex and it is not surprising therefore that some of the most successful applications of INAA in archaeology have been in the attribution of obsidian artifacts to source. Obsidian is a volcanic glass formed from a rapidly cooled molten magma that was exploited culturally to produce useful shapes without changing its composition. The application of INAA has allowed the source of obsidian artifacts to be determined, occasionally to specific obsidian flows.

Another class of archaeological material that has been the subject of intensive analysis by neutron activation is pottery. Data obtained from ceramic analyses are more complex than those of obsidian as they reflect the interaction of several factors that can be categorized as (1) variation in natural materials combined within the ceramic object and (2) potting human practices involved in the creation of the pottery (Bishop et al. 1982; see also IAEA, 2003). Ceramics are combinations of naturally occurring raw clays and silts, often with variably sorted coarser materials that may have been mixed in some customary manner, and these combinations can change spatially and over time. Preparation of the ceramic paste can involve the removal of some fraction of the naturally occurring material or the addition of other materials to "temper" the working properties of the malleable mixture so that a vessel can be formed and fired successfully. Added tempering materials can include clay of a different plasticity than the base clay, crushed fired clay, crushed pottery (grog), weathered limestone, quartz sand volcanic glass, grass and manure among others. Each material, added in variable proportions, modifies the original composition of the base clay matrix in some manner. Thus tracing the analyzed pottery back to a specific source, such as a particular clay deposit or highly delimited location along a river, may not be possible due to the effects of mixing multiple ingredients within a highly composite final product. In most cases, archaeological sourcing of pottery relies on identifying groups of ceramics that are sufficiently similar in chemical composition. These groups are used to infer a source of manufacture that is spatially and/or temporally delimited and discrete by comparison to other groups of similarly analyzed ceramics. The location of manufacture can be determined by matching the chemical composition of unsourced ceramic groups to the waster products recovered from archaeological potting workshops, but such sites are relatively rare. If the pottery being analyzed reveals a discontinuous spatial distribution, an inference may be made that it is most likely to have originated in the geographical location where it is most abundantly recovered. Exceptions, however, may occur.

There are two major considerations that follow from the preceding statement. The first one is the need to analyze reasonably large numbers of samples representing the pottery of interest; depending upon the specific problem, or question to answer sample sizes for archaeological uses may be in the low hundreds (Bishop and Blackman, 2002). Second the size of a resulting data matrix, in addition to the natural, cultural and analytical sources of variation that are represented within it, requires well-considered steps to mine the data for patterns that are meaningful for archaeological interpretation. Since data sets normally consist of several dozen to several hundred analyzed specimens, multivariate procedures are used to assess degree of resemblance among individual chemical profiles according to some chosen definition of similarity (Bishop and Neff, 1989; Neff 2002). Analytical approaches may involve the use of several pattern extraction methods involving cluster analysis, outlier identification, and group evaluation, in addition to techniques that display aspects of variation in the data (e.g., the well-known technique of principal components analysis). These techniques should be chosen based upon properties of the data are being explored and evaluated, not so much by arbitrary statistical results but with attention to how the chemical patterns covary with archaeological attributes of form, decoration, time, association, etc.

In addition to obsidian and pottery, INAA has been applied with varying degrees of success to other types of archaeological materials including unfired clay, limestone, marble, chert, turquoise, jade, native copper, steatite, and shell, among others. With all of these materials, given an adequate elemental abundance in the target material and appropriate irradiation and counting conditions, INAA is capable of producing high-quality data. Recalling that one of the great strengths of INAA is its ability to analyze a solid or bulk sample, interpretive difficulties may nevertheless arise with such bulk samples because it is difficult to know exactly what is being analyzed.

Since the 1980s, the scientific community has had to respond to economic and political pressures for greater emphasis on applied research, including research carried out with the aid of nuclear reactors (e.g., Byrne, 2001, 83). Many of the large reactor facilities that undertook neutron activation of archaeological materials (e.g., Brookhaven National Laboratory, Lawrence Berkeley National Laboratory, Hebrew University, the Slowpoke Reactor-Toronto) have now ceased to operate, and with only a few notable exceptions, archaeological reliance is slowly moving to the use of newer analytical techniques (such as inductively coupled mass spectrometry) that involve skills and knowledge in chemical analysis that are beyond the level of archaeologists. The few remaining INAA facilities capable of undertaking archaeological research (e.g., Missouri Research Reactor, National Centre of Scientific Research "Demokritos" [Greece], Oregon State University, Smithsonian-NIST facility [Gaithersburg, MD]) continue to run at full capacity, contributing to existing legacy databases that remain to be more fully mined for existing patterns that inform about the past.

Bibliography

Batchelor L, Loni A, Canham LT, Hasan M, Coffer, J. L., 2012. Manufacture of mesoporous silicon from living plants and agricultural waste: an environmentally friendly and scalable process. Silicon 4:259–266.

Bernados A, Aznar E, Coll C, Martinez-Menez R, Barat JM, Marcos MD, Sancenon F, Benito A, Soto, J., 2008. Controlled release of vitamin B" using mesoporous materials functionalized with amine-bearing gate-like scaffoldings. J Control Release 131:181–189.

Bishop, R. L., 2003. Instrumental neutron activation analysis of archaeological ceramics: progress and challenges. In *Nuclear Analytical Techniques in Archaeological Investigations*. Vienna: IAEA Technical Reports Series no. 416.Vienna: International Atomic Energy Agency, pp. 35–44.

Bishop, R. L., 2014. Instrumental approaches to understanding Mesoamerican economy: elusive promises. *Ancient Mesoamerica*, **25**(1), 251–269.

Bishop, R. L., and Blackman, M. J., 2002. Instrumental neutron activation analysis of archaeological ceramics: scale and interpretation. *Accounts of Chemical Research*, **35**(8), 603–610.

Bishop, R. L., and Neff, H., 1989. Compositional data analysis in archaeology. In Allen, R. O. (ed.), *Archaeological Chemistry IV*. New York: American Chemical Society. Advances in Chemistry Series 220, Washington, DC, pp. 57–86.

Bishop, R. L., Rands, R. L., and Holley, G., 1982. Ceramic compositional analysis in archaeological perspective. In Schiffer, M. (ed.), *Advances in Archaeological Method and Theory*. New York: Academic, Vol. 5, pp. 275–330.

Blackman, M. J., 1984. Provenance studies of Middle Eastern obsidian from sites in highland Iran. In Lambert, J. B. (ed.), *Archaeological Chemistry – III*. Washington, DC: American Chemical Society. Advances in Chemistry, Vol. 205, pp. 19–50.

Byrne, A. R., 2001. A strategy for the survival and enrichment of NAA in a wider context. In *Use of Research Reactors for Neutron Activation Analysis*. Vienna: International Atomic Energy Agency. IAEA-Tecdoc-1215, pp. 83–91.

Canham, L. T., 2007b. Food comprising silicon. International Patent WO 2007/012847.

Carlisle, E. M., 1974. Chapter 4, Silicon in bone formation. In: Simpson TL, Volcani BE (eds) Silicon and siliceous structures in biological systems. Springer, Berlin, pp 69–94.

De Corte, F., 1987. The k0-standardization Method; A Move to the Optimization of Neutron Activation Analysis. Faculteit van de Wetenschappen, Instituut voor Nucleaire Wetenschappen, Laboratorium voor Analytische Scheikunde, Rijksuniversiteit Gent. http://www.naa-online.net/practical/downloads/

Dejeneka W, L., 2003. Determination of total and bioavailable silicon in selected foodstuffs. Food Control 14:193–196.

De Soete, D., Gijbels, R., and Hoste, J., 1972. *Neutron Activation Analysis*. Chemical analysis: a series of monographs. London: Wiley-Interscience.

Djingova, R., Kuleff, I., and Penev, I., 1990. Instrumental neutron activation analysis of reference materials for archaeometric investigations of pottery. *Journal of Radioanalytical and Nuclear Chemistry*, **144**(6), 397–406.

Glascock, M., 1994. Nuclear reaction chemical analysis: prompt and delayed measurements. In Alfassi, Z. B. (ed.), *Chemical Analysis by Nuclear Methods*. Chichester: Wiley, pp. 75–99.

Harbottle, G., 1976. Activation analysis in archaeology. In Newton, G. W. A. (ed.), *Radiochemistry: A Specialist Periodical Report*. London: The Chemical Society. Radiochemistry, Vol. 3, pp. 33–72.

IAEA, 2003. *Nuclear Analytical Techniques in Archaeological Investigations*. Vienna: International Atomic Energy Agency. IAEA Technical Reports Series no. 416.

Iler, R. K., 1979. The chemistry of silica. Wiley, New York.

Kennedy, G., and St-Pierre, J., 1999. Comparison of the relative and k0 methods for the standardization of NAA with stable low-flux reactors. *Biological Trace Element Research*, **71–72**(1), 443–451.

Kim, K. J., Jeon, Y. J., Lee, J. H., Ahn, S. T., Lee, S. H., Cho, D. W., Rhie, J. W., 2010. The effect of silicon ion on proliferation and osteogenic differentiation of human ADSCs. Tissue Eng Regen Med 7(2):171–177.

Lindstrom, R. M., and Yonezawa, C., 1995. Prompt gamma activation analysis with guided neutron beams. In Alfassi, Z. B., and Chung, C. (eds.), *Prompt Gamma Neutron Activation Analysis*. Boca Raton: CRC Press, pp. 93–100.

Mojsiewicz-Pienkowska K, Lukasiak J., 2003. Analytical fractionation of silicon compounds in foodstuffs. Food Control 14:153–162.

Neff, H., 2000. Neutron activation analysis for provenance determination in archaeology. In Ciliberto, E., and Spoto, G. (eds.), *Modern Analytical Methods in Art and Archaeology*. New York: John Wiley and Sons. Chemical Analysis, Vol. 155, pp. 81–134.

Neff, H., 2002. Quantitative techniques for analyzing ceramic compositional data. In Glowacki, D. M., and Neff, H. (eds.), *Ceramic Production and Circulation in the Greater Southwest*. Los Angeles: The Cotsen Institute of Archaeology, University of California. Monograph, Vol. 44, pp. 15–36.

Rashidi, L. Vasheghani-Farakani E, Rostami K, Gangi F, Fallahpour M., 2003. Mesoporous silica nanoparticles as a nanocarrier for delivery of vitamin C. Iran J Biotechnol 11 (4):209–213.

Robberecht H, Van Dyck K, Bosscher D, Van Cauwenbergh R (2008). Silicon in foods: content and bioavailability. Int J Food Prop 11:638–645.

Schwartz, K., 1977. Silicon, fibre and atherosclerosis. Lancet 1(8009):454–457.

Seaborn, C. D, Nielsen, F. H., 1993. Silicon: a nutritional beneficence for bones, brains and blood vessels ? Nutr Today, July/August pp 13–18.

Shackley, M. S., 2005. *Obsidian: Geology and Archaeology in the North American Southwest*. Tucson: University of Arizona Press.

Shackley, M. S. (ed.), 1998. *Archaeological Obsidian Studies: Method and Theory*. New York: Plenum. Advances in Archaeological and Museum Science, Vol. 3.

Cross-references

Ceramics
Geochemical Sourcing
Inductively Coupled Plasma-Mass Spectrometry (ICP-MS)
Lead Isotopes
Lithics
X-ray Fluorescence (XRF) Spectrometry in Geoarchaeology

NIAH CAVE

Chris O. Hunt
School of Natural Sciences and Psychology, Liverpool John Moores University, Liverpool, UK

Synonyms

The Great Cave of Niah

Introduction

Niah Cave, more properly known as the Great Cave of Niah, in Sarawak, Malaysian Borneo, lies in the northern side of the Gunong Subis massif 11 km inland from the shore of the South China Sea. The cave was dug in the 1950s and 1960s by Tom and Barbara Harrisson, in the 1980s by Zuriana Majid, and between 2000 and 2004 by Graeme Barker and Tim Reynolds, with geoarchaeological work coordinated by David Gilbertson.

Geomorphology

The cave is one of several enormous, highly complex and extremely ancient caves in the Gunong Subis, a tower karst massif developed in Miocene patch reef limestones. This elevated area stands in coastal lowlands which are underlain by turbiditic mudrocks also of Miocene age. The cave displays morphological evidence for phreatic development (formation beneath the water table) followed by a long and complex history of vadose modification (above the water table).

The cave fill

The cave sediments are highly complex (Gilbertson et al., 2005, 2013; Stephens et al., 2005) and best known from the archaeological excavations and reconnaissance in the West Mouth and other entrances to the cave (Gilbertson et al., 2005, 2013). The longest sequence is in the West Mouth, where ancient, complex, highly weathered basal diamicts (poorly sorted sediments with different particle sizes), referred to as Unit (1) are overlain by clayey diamicts, sands, and silts of Unit (2C) and (2) dating from ~55,000 to ~38,000 BP and containing abundant archaeological materials including lithic artifacts, bone, shell, and charcoal. These deposits were cut and partially disrupted by a major mudflow event (Dykes, 2007) which gave rise to thick diamicts now characterized by "spots" of white secondary gypsum (Unit 3). From about 35,000 BP, silty diamicts with abundant occupation debris (Unit 4) were laid down in a basin formed by partial collapse of older deposits. Unit 4 continued to accumulate episodically until late Holocene times. From ~35,000 BP, people cut deep pits into the cave sediments. Some of these seem to have been used for detoxifying the poisonous nuts of *Pangium edule* (Malay "kepayang") since these are found in great quantities. During the latest Pleistocene and particularly the Holocene, the cave was used as a burial site.

Archaeology

The Great Cave first came to prominence in 1958 with the finding by Barbara Harrisson of the so-called Deep Skull, for many years the oldest morphologically modern human skeletal material in the world. Recent re-evaluation and U-series dating suggests that the "Deep Skull" is ~35,000 years old and may have been part of a secondary burial (Barker et al., 2007; Hunt and Barker, 2014), but the earliest human activity in the cave is estimated to be around 52,000 BP (Hunt et al., 2012). The cave was used as a habitation site during the Late Pleistocene, and the cave fill contains abundant evidence of the skill of the inhabitants in exploiting the complex, difficult, and rapidly changing ecosystems of the period, with animal bones, shell, macro-plant remains, pollen, phytoliths, and starch all very well preserved (Barker et al., 2007; Barton et al., 2009; Piper and Rabett, 2009; Barker, 2013). The cave was also used for ritual activity using human remains from ca. 45,000 BP (Hunt and Barker, 2014), and exploitation as a place of interment became its main use during the Holocene. So far, 258 burials have been investigated with excellent preservation of organic materials including hair, skin, basketry, and wood (Lloyd-Smith, 2012).

Bibliography

Barker, G. (ed.), 2013. *Rainforest Foraging and Farming in Island Southeast Asia: The Archaeology of the Niah Caves, Sarawak*. Cambridge: McDonald Institute for Archaeological Research.

Barker, G., Barton, H., Bird, M., Daly, P., Datan, I., Dykes, A., Farr, L., Gilbertson, D., Harrisson, B., Hunt, C., Higham, T., Kealhofer, L., Krigbaum, J., Lewis, H., McLaren, S., Paz, V., Pike, A., Piper, P., Pyatt, B., Rabett, R., Reynolds, T., Rose, J., Rushworth, G., Stephens, M., Stringer, C., Thompson, J., and Turney, C., 2007. The 'human revolution' in lowland tropical Southeast Asia: the antiquity and behavior of anatomically modern humans at Niah Cave (Sarawak, Borneo). *Journal of Human Evolution*, **52**(3), 243–261.

Barton, H., Piper, P. J., Rabett, R., and Reeds, I., 2009. Composite hunting technologies from the Terminal Pleistocene and Early Holocene, Niah Cave, Borneo. *Journal of Archaeological Science*, **36**(8), 1708–1714.

Dykes, A. P., 2007. Mass movements in cave sediments: investigation of a ~ 40,000-year-old guano mudflow inside the entrance of the Great Cave of Niah, Sarawak, Borneo. *Landslides*, **4**(3), 279–290.

Gilbertson, D., Bird, M., Hunt, C., McLaren, S., Mani Banda, R., Pyatt, B., Rose, J., and Stephens, M., 2005. Past human activity and geomorphological change in a guano-rich tropical cave mouth: initial interpretations of the late quaternary succession in the Great Cave of Niah, Sarawak. *Asian Perspectives*, **44**(1), 16–41.

Gilbertson, D., McLaren, S., Stephens, M., Hunt, C., Rose, J., Dykes, A., Grattan, J., Bird, M., Lewis, H., Kealhofer, L., Mani Banda, R., Badang, D., Daly, P., Rushworth, G., Pyatt, B., Thompson, G. B., Piper, P. J., and Rabbett, R., 2013. The cave entrance sequences and environmental change. Chapter 3. In Barker, G. (ed.), *Rainforest Foraging and Farming in Island Southeast Asia: The archaeology of Niah Caves, Sarawak*. Cambridge: McDonald Institute for Archaeological Research, pp. 71–134.

Hunt, C. O., and Barker, G., 2014. Missing links, cultural modernity and the dead: anatomically modern humans in the Great Cave of

Niah (Sarawak, Borneo). In Dennell, R., and Porr, M. (eds.), *Southern Asia, Australia, and Modern Human Origins*. New York: Cambridge University Press, pp. 90–107.

Hunt, C. O., and Rushworth, G., 2005. Pollen taphonomy and airfall sedimentation in a tropical cave: the West Mouth of the Great Cave of Niah in Sarawak, Malaysian Borneo. *Journal of Archaeological Science*, **32**(3), 465–473.

Hunt, C. O., Gilbertson, D. D., and Rushworth, G., 2012. A 50,000-year record of late Pleistocene tropical vegetation and human impact in lowland Borneo. *Quaternary Science Reviews*, **37**, 61–80.

Lloyd-Smith, L., 2012. Early Holocene burial practice at Niah Cave, Sarawak. *Bulletin of the Indo-Pacific Prehistory Association*, **32**, 54–69.

Piper, P. J., and Rabett, R. J., 2009. Hunting in a tropical rainforest: evidence from the terminal pleistocene at Lobang Hangus, Niah Caves, Sarawak. *International Journal of Osteoarchaeology*, **19**(4), 551–565.

Stephens, M., Rose, J., Gilbertson, D. D., and Canti, M. G., 2005. Micromorphology of cave sediments in the humid tropics: Niah Cave, Sarawak. *Asian Perspectives*, **44**(1), 42–55.

O

OLDUVAI

Gail M. Ashley
Department of Earth and Planetary Sciences, Rutgers University, Piscataway, NJ, USA

Synonyms

Oldupai (wild sisal plant); Olduvai (Maasai language); Olduvai Gorge

Olduvai Gorge is a valley incised into the Serengeti Plain in northern Tanzania. The main tributary of the Olduvai River flows 46 km eastward from lakes Masek and Ndutu to a depression, Olbalbal, at the foot of the Ngorongoro Volcanic Highland (Hay, 1976). The gorge is ~100 m deep and cuts across the Olduvai basin, exposing a two million-year-long sequence of volcaniclastic sediments interbedded with numerous tuffs that have been dated with $^{40}Ar/^{39}Ar$ radiometric dating.

Olduvai sediments contain a rich faunal and cultural record of early hominins – *Paranthropus boisei*, *Homo habilis*, and *Homo erectus* (Leakey, 1971). There are over 50 archaeological sites; the two sites with the densest concentration of stone tools, bones, and human modified bones are FLK Zinj, dating to ~1.84 Ma (Domínguez-Rodrigo et al., 2007; Ashley et al., 2010a) and BK, dating to >1.2 Ma (Domínguez-Rodrigo et al., 2009).

Paleoenvironmental studies have indicated that most of the archaeological sites are located near the margin of ancient Lake Olduvai. It was originally assumed that the lake was used by hominins as a water source (Leakey, 1971; Hay, 1976), but it is now known that the lake was saline-alkaline (toxic) and that it was a playa that fluctuated frequently in level and dried up periodically (Hay, 1976; Ashley, 2007). Recent studies show that freshwater springs were associated with many of the archaeological sites and that these springs likely attracted hominins and other vertebrates to the area of Olduvai (Ashley et al., 2010b).

Bibliography

Ashley, G. M., 2007. Orbital rhythms, monsoons and playa lake response, Olduvai Basin, equatorial East Africa (ca. 1.85–1.74 Ma). *Geology*, **35**(12), 1091–1094.

Ashley, G. M., Barboni, D., Domínguez-Rodrigo, M., Bunn, H. T., Mabulla, A. Z. P., Diez-Martín, F., Barba, R., and Baquedano, E., 2010a. A spring and wooded habitat at FLK Zinj and their relevance to origins of human behavior. *Quaternary Research*, **74**(3), 304–314.

Ashley, G. M., Domínguez-Rodrigo, M., Bunn, H. T., Mabulla, A. Z. P., and Baquedano, E., 2010b. Sedimentary geology and human origins: a fresh look at Olduvai Gorge, Tanzania. *Journal of Sedimentary Research*, **80**(3), 703–709.

Domínguez-Rodrigo, M., Barba, R., and Egelund, C. P., 2007. *Deconstructing Olduvai: A Taphonomic Study of the Bed I Sites*. Dordrecht: Springer. Vertebrate Paleobiology and Paleoanthropology Series.

Domínguez-Rodrigo, M., Mabulla, A., Bunn, H. T., Barba, R., Diez-Martín, F., Egeland, C. P., Espílez, E., Egeland, A., Yravedra, J., and Sánchez, P., 2009. Unraveling hominin behavior at another anthropogenic site from Olduvai Gorge (Tanzania): new archaeological and taphonomic research at BK, Upper Bed II. *Journal of Human Evolution*, **57**(3), 260–283.

Hay, R. L., 1976. *Geology of the Olduvai Gorge*. Berkeley: University of California Press.

Leakey, M. D., 1971. *Olduvai Gorge: Excavations in Beds I and II, 1960–1963*. Cambridge: Cambridge University Press.

Cross-references

$^{40}Ar/^{39}Ar$ and K–Ar Geochronology
Landscape Archaeology
Paleoenvironmental Reconstruction
Sedimentology
Spring Settings

A.S. Gilbert (ed.), *Encyclopedia of Geoarchaeology*, DOI 10.1007/978-1-4020-4409-0,

OPTICALLY STIMULATED LUMINESCENCE (OSL) DATING

Zenobia Jacobs
School of Environmental and Earth Sciences, University of Wollongong, Wollongong, NSW, Australia

Synonyms

Green-light stimulated luminescence (GLSL); Infrared stimulated luminescence (IRSL); Optical dating; Photon-stimulated luminescence (PSL); Photonic dating

Definition

Optical: Relating to the use of visible or near-visible light

Stimulated: To excite with a stimulus (light or heat)

Luminescence: The emission of light

Optically stimulated luminescence: The emission of light from crystalline materials when stimulated by light following previous absorption of energy from radiation

Introduction

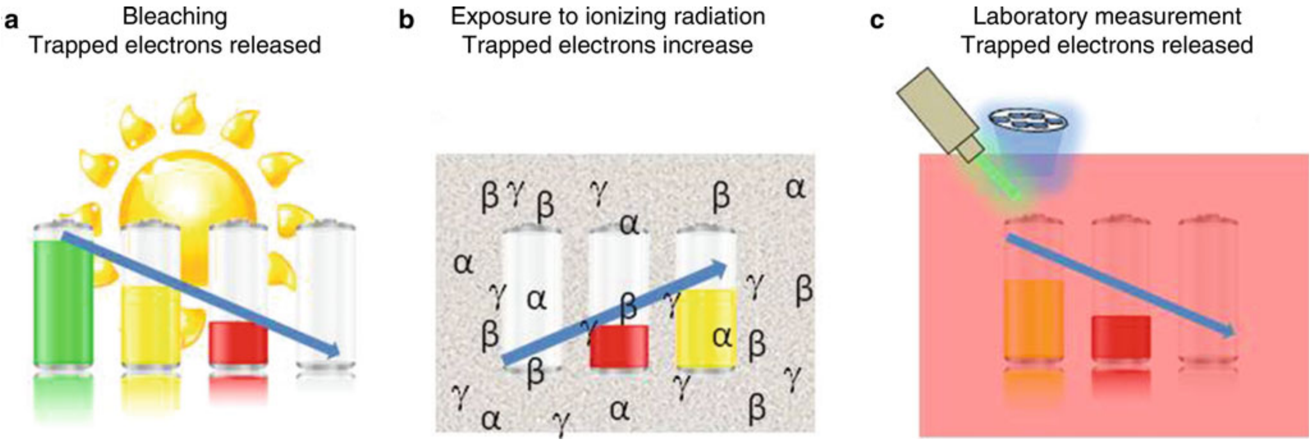
Luminescence dating consists of a family of analytical methods, most of which are used in archaeological research. They can be applied to samples ranging in age from just a few years to several hundreds of thousands of years (beyond the range of radiocarbon dating), and they are, therefore, able to cover a time interval that includes important turning points in the evolution of humans. The choice of luminescence method depends on the availability of appropriate minerals, the time period of interest, and the nature of the target event. When one technique is not suitable to a particular situation, another technique often is. The basic principles of all the different luminescence dating techniques, and also electron spin resonance (ESR) dating, are the same: each relies on the effects of radiation exposure. Ages are obtained by measuring the cumulative effect of ionizing radiation on the crystal structure of certain minerals. The longer the duration since first exposure to radiation, the greater the amount of energy absorbed, and consequently, the greater the luminescent signal obtained, which is indicative of an older age for the material being investigated. The physical basis has been discussed in detail for the nonspecialist by Feathers (1996) and Wintle (2008) and for the specialist by Aitken (1985, 1998) and Bøtter-Jensen et al. (2003). Recent advances in luminescence dating of sediments and applications in the earth and archaeological sciences have been described by Feathers (2003), Duller (2004), Lian and Roberts (2006), Lian (2007), Jacobs and Roberts (2007), and Roberts et al. (2015). The impact of luminescence dating in archaeology was demonstrated in two comprehensive review papers by Roberts (1997) and Wintle (2008). The former covered early work on sites in Africa, Western Europe, East Asia, Siberia, Australia, and the Americas, whereas the latter reviewed the more recent applications as part of a history of the last 50 years of luminescence dating in archaeology.

OSL

Optically stimulated luminescence (OSL) dating of sedimentary quartz grains and thermoluminescence (TL) dating of burnt stones are the methods most commonly applied in archaeological contexts, and the former is the subject of this entry. The use of OSL dating was first proposed by Huntley et al. (1985). OSL dating of sediments yields an estimate of the time since mineral grains, such as quartz or feldspars, were last exposed to sunlight. In this instance, the duration of burial in the absence of sunlight can provide ages for site occupation, the manufacture of artifacts, and the accumulation of faunal remains, all inferred from the depositional age of the associated surrounding sediments being dated. The first archaeological application was published by Rhodes (1988), who used the method to analyze quartz grains from three archaeological sites (Chaperon Rouge, Skhirat, and Tahadart) in Morocco. OSL dating can also be applied to heated materials, such as burnt stones and pottery, but TL dating remains the method of choice for such materials. Bøtter-Jensen and Duller (1992) were the first to date heated materials by OSL when they dated quartz grains extracted from burnt stone at a Viking Age site in Sweden.

Age determination

The OSL dating technique is based on the fact that natural minerals (such as quartz and feldspar) are not perfectly formed but contain defects in their crystal lattices that are able to trap negatively charged electrons within positively charged vacancies (“holes”). These mineral grains can be likened to rechargeable batteries (Figure 1). While buried, the mineral grains are exposed to a low-level flux of naturally occurring ionizing radiation resulting from the nuclear decay of potassium (^{40}K), rubidium (^{87}Rb), uranium (^{238}U and ^{235}U and their decay products), and thorium (^{232}Th and its decay products) from within the sample and also external to the sample in the surrounding soil. Cosmic radiation also contributes a small amount. While buried in the ground and hidden from sunlight, these “batteries” trap and store electrons as particles emitted from unstable radioactive atoms move them out of their normal orbital locations. In this way, the trapped electrons become more numerous and accumulate energy at a predictable rate over time (Figure 1b). If the sediment is transported by wind or water and the “batteries” are exposed to sunlight, they lose their charge in a matter of seconds (Godfrey-Smith et al., 1988), thereby emptying the battery; the luminescence “clock” is thus set to zero (Figure 1a), and once the sediments are again buried, they “recharge” by the same process. Likewise, the same would happen if the sediments were heated to high temperatures (>400 °C). When these sediments are subsequently



Optically Stimulated Luminescence (OSL) Dating, Figure 1 A rechargeable battery serves as a useful analogy for how mineral grains behave as natural dosimeters in OSL dating. When mineral grains are exposed to sunlight (**a**) or heat, trapped electrons are released, a process called bleaching that resets the luminescence "clock." Once the mineral grains are buried and hidden from sunlight again, the grains are reexposed to natural ionizing radiation (alpha, beta, gamma, and cosmic in origin) and become recharged (**b**). Once the sediment sample has been collected and taken back to the laboratory, the mineral grains can be stimulated with a green laser or blue light-emitting diode, which will release the trapped electrons in the form of light emission (*OSL*) that can then be measured (**c**).

cooled and deposited within accumulating sediments, e.g., within a cave, they once again become hidden from sunlight, and the "batteries" begin to recharge (Figure 1b). In other words, natural radiation sources in the immediate vicinity of the grains will result in the movement of new electrons out of their orbitals and into traps, with the rate of filling being determined by the level of natural radiation.

To determine an OSL age, the following equation is used:

$$\text{Age estimate}(ka) = \frac{\text{Equivalent dose } (D_e)(Gy)}{\text{Estimated environmental dose rate}(Gy/ka)}$$

where D_e (equivalent dose) corresponds to the radiation dose absorbed by the mineral grains since they were last exposed to sunlight or heat, Gy (or gray) is a unit of radiation absorption equal to 1 J of radiation per kg of sample, and ka is 1,000 years. The environmental dose rate refers to the rate of supply of ionizing radiation to the mineral grains from environmental sources. Further details about how these two parameters are estimated are discussed below.

Sample collection and preparation

To estimate the D_e of a sample, the sediments must be collected in the dark. This prevents exposure of the grains to light, a process known as bleaching, which would lead to the light-sensitive OSL traps being emptied and the OSL "clock" being reset. There are many ways of collecting OSL samples. The most typical would be to hammer opaque plastic or metal tubes into a cleaned section wall; the sediment at both ends of the tube will then be discarded in the lab, and the inner light-safe portion will be used for the measurement of the OSL signal. Alternatively, samples can be collected by scraping sediment into black light-tight bags while covered by a black tarpaulin to keep light out; a red-light torch can be used for illumination since red wavelengths do not affect the electron traps. Or samples can be collected at night also with the aid of a red-light torch.

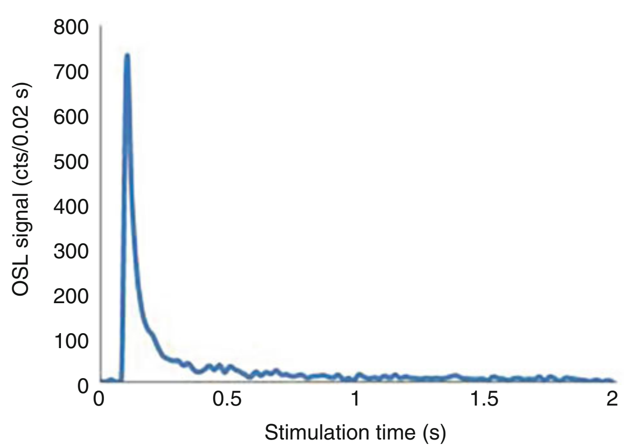
The samples are then transported to a suitable luminescence laboratory where the OSL measurements are made on mineral grains extracted from the bulk sediment sample. The lighting level in the luminescence laboratory is low and usually red, similar to the conditions in a photographic darkroom. The grains, 90–300 μm in diameter (sand sized), are usually extracted from the bulk sediment sample by wet or dry sieving and are then chemically treated with hydrochloric (HCl) acid to remove carbonates and hydrogen peroxide (H_2O_2) solution to digest any organic matter. The mineral grains are then suspended in heavy liquids, such as sodium polytungstate, at specific densities to remove heavy minerals, such as zircons, and to separate quartz and potassium feldspars. In addition, the sand-sized grains are chemically etched in hydrofluoric (HF) acid to remove the outer surface of each grain. The grains are then sieved again to provide a narrow range of sizes (e.g., 180–212 μm diameter) and mounted in a monolayer on a 9.8 mm diameter stainless steel or aluminum disk, which has been pre-sprayed with silicone oil so that the grains stay adhered during the measurement procedure. In the case of single-grain dating, each grain is placed in an individual hole drilled into the surface of an aluminum disk, each disk designed to hold 100 single grains. Selection of specific grain sizes is important as this allows calculation of the relative contributions of alpha and beta radiation to the grains in their natural environment.

Equivalent dose (D_e) determination

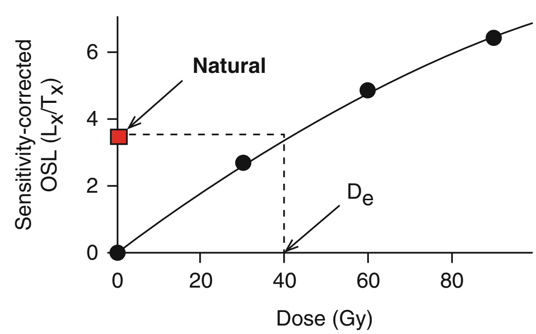
Once in the laboratory, the trapped electrons can be released by stimulating the quartz grains with blue or green light (or infrared radiation if the mineral is potassium-rich feldspar) (Figure 1c). This release, and the subsequent physical processes inside the crystal, results in the emission of OSL, which decreases in intensity during the stimulation time as the light-sensitive traps are quickly and progressively emptied. The resulting plot of the OSL signal decrease versus stimulation time is known as an OSL decay curve (Figure 2). The OSL signal from the as-collected (natural) sample is related to the number of electrons that have populated the light-sensitive traps since they were last emptied; it is, therefore, related to the time elapsed since the grains were last exposed to sunlight. The D_e is the radiation dose required in the laboratory to produce an OSL signal of the same intensity as the natural OSL. It is estimated by comparing the natural OSL signal just obtained with those obtained from the same now bleached sample after it receives a series of calibrated radiation doses in the laboratory using a $^{90}Sr/^{90}Y$ beta source or, less commonly, a gamma- or X-ray source. These subsequent laboratory exposures to radiation are regenerative doses designed to find the dose that delivers an equivalent natural OSL signal. The resulting plot of OSL intensity versus laboratory dose is known as a dose-response curve, or growth curve (Figure 3). The D_e is estimated by projecting the natural OSL signal onto this curve, and the intercept – the D_e – is expressed in Gy, which is the SI unit for absorbed radiation dose.

To obtain useful information regarding the burial time of quartz grains, the OSL signal must be converted into a reliable estimate of the D_e. Over the last decade, methodological and technological developments have shifted the emphasis from using multiple-aliquot procedures to determine the D_e (Feathers, 1996; Lian and Roberts, 2006) to measuring the D_e for individual aliquots composed, typically, of tens, hundreds, or thousands of grains. An aliquot is the sample of grains mounted on a disk; the size of the aliquot can be changed, and an extreme case of single-aliquot dating is when each aliquot consists of just one grain (Duller, 2008). Multiple-aliquot methods require the use of many aliquots (e.g., 24 or more) to produce a single estimate of the sample D_e, whereas single-aliquot and, hence, single-grain measurements require only one aliquot or one grain, to yield an estimate of D_e. In other words, the entire dose-response curve shown in Figure 3 is constructed on the basis of one grain or aliquot, whereas at least five different aliquots would be needed to construct the same curve using the multiple-aliquot approach. A key benefit of the single-aliquot approach is that replicate measurements of D_e can be generated for the same sample. It is typical to measure 24 or more multigrain single aliquots or many hundreds of single grains. These provide an internal check on the reproducibility of results, thereby facilitating the recognition of sample contamination and other problems that may need to be addressed before final age determination. For sediments that have been exposed only briefly to sunlight before burial or that have suffered from postdepositional disturbance, the most accurate OSL ages will be obtained by using single-aliquot and single-grain methods along with appropriate statistical procedures (e.g., Galbraith et al., 1999; Roberts et al., 2000; Jacobs and Roberts, 2007).

Two principal methods have been proposed for measuring the D_e using single aliquots or single grains of quartz:



Optically Stimulated Luminescence (OSL) Dating, Figure 2 An OSL decay curve observed from the luminescence emitted by an individual quartz grain upon stimulation by a green laser beam. The OSL signal drops rapidly as a function of time as electron traps empty when exposed to laser light.



Optically Stimulated Luminescence (OSL) Dating, Figure 3 An OSL dose-response curve, or growth curve, constructed for an individual quartz grain using the single-aliquot regenerative-dose (*SAR*) procedure to estimate the D_e. The natural OSL signal is denoted by the *red square* on the y-axis, and the *black circles* are the signals induced by repeated and varying laboratory doses, to which the dose-response curve has been fitted using a saturating exponential.

the single-aliquot additive dose protocol (Murray et al., 1997) and the single-aliquot regenerative-dose (SAR) procedure (Murray and Roberts, 1998; Murray and Wintle, 2000; Wintle and Murray, 2006). The latter procedure is currently the preferred approach because the D_e is obtained by interpolation rather than by extrapolation of the dose-response curve. This results in more accurate and precise estimates. The SAR procedure also has several other attractive features. It takes account of sensitivity changes that commonly occur during laboratory heating procedures and that may have occurred during the burial period. It also contains various internal checks that allow routine testing of the performance of the SAR protocol for any specific sample and the rejection of aliquots or grains that fail these checks (Wintle and Murray, 2006; Jacobs et al., 2006). Tests can also be made to confirm the suitability of the experimental conditions applied to the dated grains, such as the ability of the SAR protocol to recover the correct dose from grains that have been deliberately bleached and then given a known laboratory dose (Roberts et al., 1999) and to minimize the complicating effect of other luminescence minerals such as feldspars (Duller, 2003). Application of the SAR protocol to individual grains, in particular, enables a statistically significant number of D_e values to be generated. By examining the structure of the resulting D_e distributions, insights can be obtained about potential complications, such as incomplete bleaching and sediment mixing, so that a high degree of confidence can be placed in the final OSL age determinations (e.g., Jacobs and Roberts, 2007).

Dose rate determination

The dose rate is usually expressed in units of grays per thousand years (Gy/ka). The total dose rate represents the sum of the contributions from uranium and thorium and their decay products together with potassium, rubidium, and a minor contribution from cosmic rays. These radioactive elements are present at low concentrations in most sediment, and their radioactive decay gives rise to alpha and beta particles and gamma rays. The distance of influence of alpha particles is very short (less than 0.02 mm), whereas beta particles can travel 2–3 mm through most sediments, gamma rays can penetrate up to 30 cm, and cosmic rays many tens of meters (Aitken, 1985, 1998). For purposes of dating, the internal dose rate of quartz or potassium-rich feldspar grains should be estimated together with the external dose rate that consists of the alpha, beta, and gamma radiation emitted by the materials surrounding the dated grains, as well as the cosmic-ray dose rate. Uranium and thorium are commonly present at low concentrations inside quartz grains, typically giving rise to an internal dose rate of 0.02–0.05 Gy/ka, whereas potassium-rich feldspar grains have a significant internal contribution from potassium, amounting to ~0.6–0.9 Gy/ka, depending on the size of the grain. These internal dose rates are most often assumed, rather than measured for each sample. The external alpha contributions are typically removed from consideration when dating sand-sized grains by etching away their outer 0.02 mm rinds using HF acid.

The cosmic dose rate is estimated using an equation provided by Prescott and Hutton (1994) that incorporates positional information on the geomagnetic latitude, altitude, and depth and density of sediment, rock, and water overburden averaged over the burial period of the sample. The remaining external dose rates from beta and gamma radiation can be measured in either of two ways: chemical or emission counting methods. Chemical methods such as neutron activation analysis (NAA), X-ray fluorescence (XRF), atomic absorption spectroscopy (AAS), and inductively coupled plasma-mass spectrometry (ICP-MS) can be used. These methods typically measure the parent radionuclide at the top of the decay series of ^{238}U and ^{232}Th. Very little (<2 %) of the gamma dose rate and <40 % of the beta dose rate delivered to the grains are derived from the parent nuclide in the uranium series. Relying on measurement of the parent concentration to obtain accurate estimates of the dose rate would be viable only if one can demonstrate that there is no disequilibrium in the uranium and thorium decay chains. Disequilibria occur when the parent and daughter radionuclides are not present in equal activities, and this can arise because the parent and several of the daughter products in the ^{238}U chain, in particular, are prone to migrate under certain geochemical conditions (Ivanovich and Harmon, 1992). Disequilibria in the uranium series are commonplace in the surficial environment, and some situations have resulted in the dose rate changing over time, which requires corrections to be made to the measured (modern-day) dose rate (Olley et al., 1996, 1997). The impact of such time-dependent changes can be minimized by using (1) emission counting techniques that can measure the parent and daughter nuclides individually, such as high-resolution gamma spectrometry and alpha spectrometry, and (2) techniques that can measure the daughter nuclides lower down the decay chain in the case of the gamma dose rate using, for example, in situ gamma spectrometry, or (3) by measuring the total radioactivity emitted by the parent and daughter products in the case of the beta dose rate, using techniques such as beta counting and thick source alpha counting.

There are also spatial variations in the beta and gamma dose rates that require consideration in some situations. For example, limestone caves may contain occasional blocks and clasts of roof spall scattered among the archaeological sediments. Lumps of limestone are comparatively free of radioactivity, so it is necessary to account for their lower gamma-ray contribution to the total dose rate; this is achieved most commonly by in situ measurement of the gamma dose rate either using TLD (thermoluminescence dosimetry) capsules or a field gamma spectrometer. The same caution, and solution, applies to samples collected less than 30 cm from the boundaries of sediment units that have markedly different dose rates.

The beta-, gamma-, and cosmic-ray dose rates also require adjustment for the long-term water content of the sample, which can be estimated from its present-day moisture content and water-holding capacity, as well as probable moisture fluctuations over the period of sample burial. A 1 % decrease in water content results in ≈1 % increase in dose rate and ≈1 % decrease in age for many quartz-containing sediments. It is usually possible to accommodate all likely long-term variations in the uncertainty term attached to the water content estimate. This uncertainty is reflected in the total uncertainty assigned to the OSL age. Uncertainties on OSL ages are typically reported at 1σ (standard error) and are calculated by combining in quadrature the total uncertainties on the D_e and dose rate estimates, each of which includes not only random but systematic errors too, unlike many other dating methods.

Applications

OSL dating is now applied routinely in archaeology (Roberts, 1997; Feathers, 2003; Wintle, 2008; Roberts and Lian, 2015) and has had a major impact on archaeology, particularly for the period beyond the limit of ^{14}C dating. It has also proven useful for deposits that lack suitable materials for ^{14}C dating. Some examples include OSL dating of possible early evidence for the exodus of modern humans out of Africa (Petraglia et al., 2007; Armitage et al., 2011; Rose et al., 2011), OSL dating of the earliest known evidence for modern human behavior (Henshilwood et al., 2002, 2011; Bouzouggar et al., 2007; Marean et al., 2007), the calculation of start and end dates and duration of two important Middle Stone Age industries – the Howiesons Poort and Still Bay – across Southern Africa (Jacobs et al., 2008), the age and duration of the Aterian of the Maghreb (Barton et al., 2009; Schwenninger et al., 2010; Jacobs et al., 2011, 2012), and the oldest artifacts and human remains discovered in Australia (Roberts et al., 1994; Bowler et al., 2003).

Bibliography

Aitken, M. J., 1985. *Thermoluminescence Dating*. London: Academic.

Aitken, M. J., 1998. *An Introduction to Optical Dating: The Dating of Quaternary Sediments by the Use of Photon-Stimulated Luminescence*. Oxford: Oxford University Press.

Armitage, S. J., Jasim, S. A., Marks, A. E., Parker, A. G., Usik, V. I., and Uerpmann, H.-P., 2011. The southern route "out of Africa": evidence for an early expansion of modern humans into Arabia. *Science*, **331**(6016), 453–456.

Barton, R. N. E., Bouzouggar, A., Collcutt, S. N., Schwenninger, J.-L., and Clark-Balzan, L., 2009. OSL dating of the Aterian levels at Dar es-Soltan I (Rabat, Morocco) and implications for the dispersal of modern *Homo sapiens*. *Quaternary Science Reviews*, **28** (19–20), 1914–1931.

Bøtter-Jensen, L., and Duller, G. A. T., 1992. A new system for measuring optically stimulated luminescence from quartz samples. *International Journal of Radiation Applications and Instrumentation. Part D. Nuclear Tracks and Radiation Measurements*, **20**(4), 549–553.

Bøtter-Jensen, L., McKeever, S. W. S., and Wintle, A. G., 2003. *Optically Stimulated Luminescence Dosimetry*. Amsterdam: Elsevier Science.

Bouzouggar, A., Barton, N., Vanhaeren, M., d'Errico, F., Collcutt, S., Higham, T., Hodge, E., Parfitt, S., Rhodes, E., Schwenninger, J.-L., Stringer, C., Turner, E., Ward, S., Moutmir, A., and Stambouli, A., 2007. 82,000-year-old shell beads from North Africa and implications for the origins of modern human behavior. *Proceedings of the National Academy of Sciences*, **104**(24), 9964–9969.

Bowler, J. M., Johnston, H., Olley, J. M., Prescott, J. R., Roberts, R. G., Shawcross, W., and Spooner, N. A., 2003. New ages for human occupation and climatic change at Lake Mungo, Australia. *Nature*, **421**(6925), 837–840.

Duller, G. A. T., 2003. Distinguishing quartz and feldspar in single grain luminescence measurements. *Radiation Measurements*, **37**(2), 161–165.

Duller, G. A. T., 2004. Luminescence dating of Quaternary sediments: recent advances. *Journal of Quaternary Science*, **19**(2), 183–192.

Duller, G. A. T., 2008. Single-grain optical dating of Quaternary sediments: why aliquot size matters in luminescence dating. *Boreas*, **37**(4), 589–612.

Feathers, J. K., 1996. Luminescence dating and modern human origins. *Evolutionary Anthropology*, **5**(1), 25–36.

Feathers, J. K., 2003. Use of luminescence dating in archaeology. *Measurement Science and Technology*, **14**, 1493–1509.

Galbraith, R. F., Roberts, R. G., Laslett, G. M., Yoshida, H., and Olley, J. M., 1999. Optical dating of single grain and multiple grains of quartz from Jinmium rock shelter, Northern Australia: part I, experimental design and statistical models. *Archaeometry*, **41**(2), 339–364.

Godfrey-Smith, D. I., Huntley, D. J., and Chen, W.-H., 1988. Optical dating studies of quartz and feldspar sediment extracts. *Quaternary Science Reviews*, **7**(3–4), 373–380.

Henshilwood, C. S., d'Errico, F., Yates, R., Jacobs, Z., Tribolo, C., Duller, G. A. T., Mercier, N., Sealy, J. C., Valladas, H., Watts, I., and Wintle, A. G., 2002. Emergence of modern human behavior: Middle Stone Age engravings from South Africa. *Science*, **295**(5558), 1278–1280.

Henshilwood, C. S., d'Errico, F., van Niekerk, K. L., Coquinot, Y., Jacobs, Z., Lauritzen, S.-E., Menu, M., and García-Moreno, R., 2011. A 100,000-year-old ochre-processing workshop at Blombos Cave, South Africa. *Science*, **334**(6053), 219–222.

Huntley, D. J., Godfrey-Smith, D. I., and Thewalt, M. L. W., 1985. Optical dating of sediments. *Nature*, **313**(5998), 105–107.

Ivanovich, M., and Harmon, R. S., 1992. *Uranium-Series Disequilibrium: Applications to Earth, Marine, and Environmental Sciences*, 2nd edn. Oxford: Oxford University Press.

Jacobs, Z., and Roberts, R. G., 2007. Advances in optically stimulated luminescence dating of individual grains from archeological deposits. *Evolutionary Anthropology*, **16**(6), 210–223.

Jacobs, Z., Duller, G. A. T., and Wintle, A. G., 2006. Interpretation of single grain D_e distributions and calculation of D_e. *Radiation Measurements*, **41**(3), 264–277.

Jacobs, Z., Roberts, R. G., Galbraith, R. F., Deacon, H. J., Grün, R., Mackay, A., Mitchell, P., Vogelsang, R., and Wadley, L., 2008. Ages for the Middle Stone Age of southern Africa: implications for human behavior and dispersal. *Science*, **322**(5902), 733–735.

Jacobs, Z., Meyer, M. C., Roberts, R. G., Aldeais, V., Dibble, H., and El Hajraoui, M. A., 2011. Single-grain OSL dating at La Grotte des Contrebandiers ('Smugglers' Cave'), Morocco: improved age constraints for the Middle Paleolithic levels. *Journal of Archaeological Science*, **38**(12), 3631–3643.

Jacobs, Z., Roberts, R. G., Nespoulet, R., Debénath, A., and El Hajraoui, M. A., 2012. Single-grain OSL chronologies for Middle Palaeolithic deposits at El Mnasra and El Harhoura

2, Morocco: implications for Late Pleistocene human-environment interactions along the Atlantic coast of northwest Africa. *Journal of Human Evolution*, **62**(3), 377–394.
Lian, O. B., 2007. Optically-stimulated luminescence. In Elias, S. (ed.), *Encyclopedia of Quaternary Science*. Amsterdam: Elsevier, pp. 1491–1505.
Lian, O. B., and Roberts, R. G., 2006. Dating the Quaternary: progress in luminescence dating of sediments. *Quaternary Science Reviews*, **25**(19–20), 2449–2468.
Marean, C. W., Bar-Matthews, M., Bernatchez, J., Fisher, E., Goldberg, P., Herries, A. I. R., Jacobs, Z., Jerardino, A., Karkanas, P., Minichillo, T., Nilssen, P. J., Thompson, E., Watts, I., and Williams, H. M., 2007. Early human use of marine resources and pigment in South Africa during the Middle Pleistocene. *Nature*, **449**(7164), 905–908.
Murray, A. S., and Roberts, R. G., 1998. Measurement of the equivalent dose in quartz using a regenerative-dose single-aliquot protocol. *Radiation Measurements*, **29**(5), 503–515.
Murray, A. S., and Wintle, A. G., 2000. Luminescence dating of quartz using an improved single-aliquot regenerative-dose protocol. *Radiation Measurements*, **32**(1), 57–73.
Murray, A. S., Roberts, R. G., and Wintle, A. G., 1997. Equivalent dose measurements using a single aliquot of quartz. *Radiation Measurements*, **27**(2), 171–184.
Olley, J., Murray, A., and Roberts, R. G., 1996. The effects of disequilibria in the uranium and thorium decay chains on burial dose rates in fluvial sediments. *Quaternary Science Reviews*, **15**(7), 751–760.
Olley, J. M., Roberts, R. G., and Murray, A. S., 1997. Disequilibria in the uranium decay series in sedimentary deposits at Allen's Cave, Nullarbor Plain, Australia: implications for dose rate determinations. *Radiation Measurements*, **27**(2), 433–443.
Petraglia, M., Korisettar, R., Boivin, N., Clarkson, C., Ditchfield, P., Jones, S., Koshy, J., Lahr, M. M., Oppenheimer, C., Pyle, D., Roberts, R., Schwenninger, J.-L., Arnold, L., and White, K., 2007. Middle Paleolithic assemblages from the Indian subcontinent before and after the Toba super-eruption. *Science*, **317**(5834), 114–116.
Prescott, J. R., and Hutton, J. T., 1994. Cosmic ray contributions to dose rates for luminescence and ESR dating: large depths and long-term time variations. *Radiation Measurements*, **23**(2–3), 497–500.
Rhodes, E. J., 1988. Methodological considerations in the optical dating of quartz. *Quaternary Science Reviews*, **7**(3–4), 395–400.
Roberts, R. G., 1997. Luminescence dating in archaeology: from origins to optical. *Radiation Measurements*, **27**(5–6), 819–892.
Roberts, R. G., and Lian, O. B., 2015. Dating techniques: illuminating the past. *Nature*, **520**(7548), 438–439.
Roberts, R. G., Jones, R., Spooner, N. A., Head, M. J., Murray, A. S., and Smith, M. A., 1994. The human colonisation of Australia: optical dates of 53,000 and 60,000 years bracket human arrival at Deaf Adder Gorge, Northern Territory. *Quaternary Science Reviews*, **13**(5–7), 575–583.
Roberts, R. G., Galbraith, R. F., Olley, J. M., Yoshida, H., and Laslett, G. M., 1999. Optical dating of single and multiple grains of quartz from Jinmium rock shelter, northern Australia: part II, results and implications. *Archaeometry*, **41**(2), 365–395.
Roberts, R. G., Galbraith, R. F., Yoshida, H., Laslett, G. M., and Olley, J. M., 2000. Distinguishing dose populations in sediment mixtures: a test of single-grain optical dating procedures using mixtures of laboratory-dosed quartz. *Radiation Measurements*, **32**(5–6), 459–465.
Roberts, R. G., Jacobs, Z., Li, B., Jankowski, N. R., Cunningham, A. C., and Rosenfeld, A. B., 2015. Optical dating in archaeology: thirty years in retrospect and grand challenges for the future. *Journal of Archaeological Science*, **56**, 41–60.
Rose, J. I., Usik, V. I., Marks, A. E., Hilbert, Y. H., Galletti, C. S., Parton, A., Geiling, J. M., Černý, V., Morley, M. W., and Roberts, R. G., 2011. The Nubian Complex of Dhofar, Oman: an African Middle Stone Age industry in southern Arabia. *PloS One*, **6**(11), e28239.
Schwenninger, J.-L., Collcutt, S. N., Barton, R. N. E., Bouzouggar, A., Clark Balzan, L., El Hajraoui, M. A., Nespoulet, R., and Debénath, A., 2010. A new luminescence chronology for Aterian cave sites on the Atlantic coast of Morocco. In Garcea, E. A. A. (ed.), *South-Eastern Mediterranean Peoples Between 130,000 and 10,000 Years Ago*. Oxford: Oxbow Books, pp. 18–36.
Wintle, A. G., 2008. Fifty years of luminescence dating. *Archaeometry*, **50**(2), 276–312.
Wintle, A. G., and Murray, A. S., 2006. A review of quartz optically stimulated luminescence characteristics and their relevance in single-aliquot regeneration dating protocols. *Radiation Measurements*, **41**(4), 369–391.

Cross-references

Electron Spin Resonance (ESR) in Archaeological Context
Inductively Coupled Plasma-Mass Spectrometry (ICP-MS)
Luminescence Dating of Pottery and Bricks
Neutron Activation Analysis
Radiocarbon Dating
X-ray Fluorescence (XRF) Spectrometry in Geoarchaeology

ORGANIC RESIDUES

Michael W. Gregg
Department of Anthropology, St. Francis Xavier University, Antigonish, NS, Canada

Definitions

Organic residues are carbon-based substances of biological origin that may survive in a broad range of archaeological contexts, including the fabric of pottery vessels, food preparation and floor surfaces, midden or latrine deposits, and archaeological sediments themselves.

Biomarkers are unique molecular compounds or distributions of compounds surviving in archaeological materials that can be matched with those of modern plant and animal species or hydrocarbons from known geological sources.

Introduction

The recovery and characterization of organic residues surviving at archaeological sites is becoming an increasingly effective means of identifying economic activities and subsistence practices associated with different prehistoric and historic cultural and technological traditions. Organic residues provide not only direct evidence of procurement and utilization of resources, but they also hold the promise of answering myriad questions that have long puzzled archaeologists using more conventional methods of inquiry (Jones, 2001; Pollard et al., 2007; Pollard and Heron, 2008; Evershed, 2008; Gregg, 2010). Yet, the possibility of gaining new insights into long-standing archaeological questions through chemical analysis of organic residues is dependent upon the limitations of current recovery protocols and instrumental analytical techniques as well as the diagnostic potential of the materials being examined.

Researchers have been interested in investigating the chemical properties of materials recovered from archaeological sites for more than 150 years, with early studies initially seeking to identify the chemical elements of pottery fabrics and clay sources (Brongniart, 1844; Richards, 1895) and later ones attempting to isolate the organic compounds that may have once have been contained within ceramic vessels (Berthelot, 1906). Overviews of these early wet-chemistry investigations can be found in Caley (1951, 1967), Rice (1987), Pollard et al. (2007), and Pollard and Heron (2008), but three of these initial studies are worth mentioning specifically because the principles used in separating the component molecules in archaeological residues from one another were established in the early twentieth century.

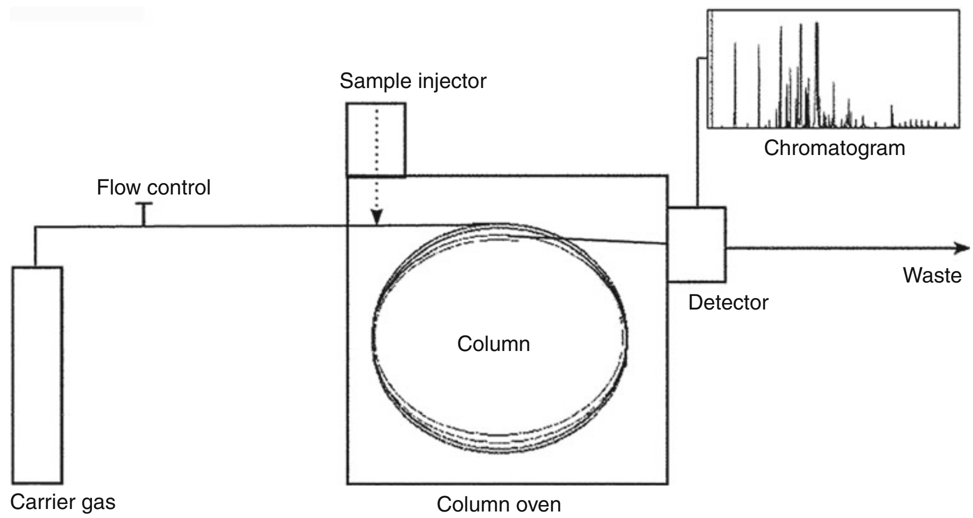
French chemist Marcellin Berthelot (1906) was the first researcher to attempt to characterize fatty acids surviving in the dregs of two Gallo-Roman vessels through the application of an alkali and organic solvent protocol to residues and subsequent separation of the solid and liquid portions through blotting paper filtration. Berthelot (1906, 128–129) claimed to have matched the proportions of palmitic ($C_{16:0}$), stearic ($C_{18:0}$), and oleic ($C_{18:1}$) free fatty acids surviving in the residue to those of olive oil. (The number of carbon atoms and type of bonds holding long chains of carbon atoms together in saturated and unsaturated fatty acids are designated with subscript notations following the symbol for carbon, such that a saturated fatty acid such as $C_{18:0}$ has 18 carbon atoms and no double bonds, whereas an unsaturated fatty acid such as $C_{18:1}$ contains a single double bond in the middle of the carbon chain.) The methods Berthelot used in his recovery and quantification remain unclear, however, and we now know these compounds can serve as evidence for the presence of both degraded animal fats and plant oils.

Later, Sir Leonard Woolley sought the assistance of petroleum chemists in identifying bitumen residues at the ancient city of Ur in southern Mesopotamia. In their sequential application of different organic solvents to solid amorphous lumps and rings found at Ur, Hackford et al. (1931) and Forbes (1936) were able to separate organic petrocarbon compounds from the asphaltene mineral fraction and imbedded reeds and rushes and measure the different components by weight and volume.

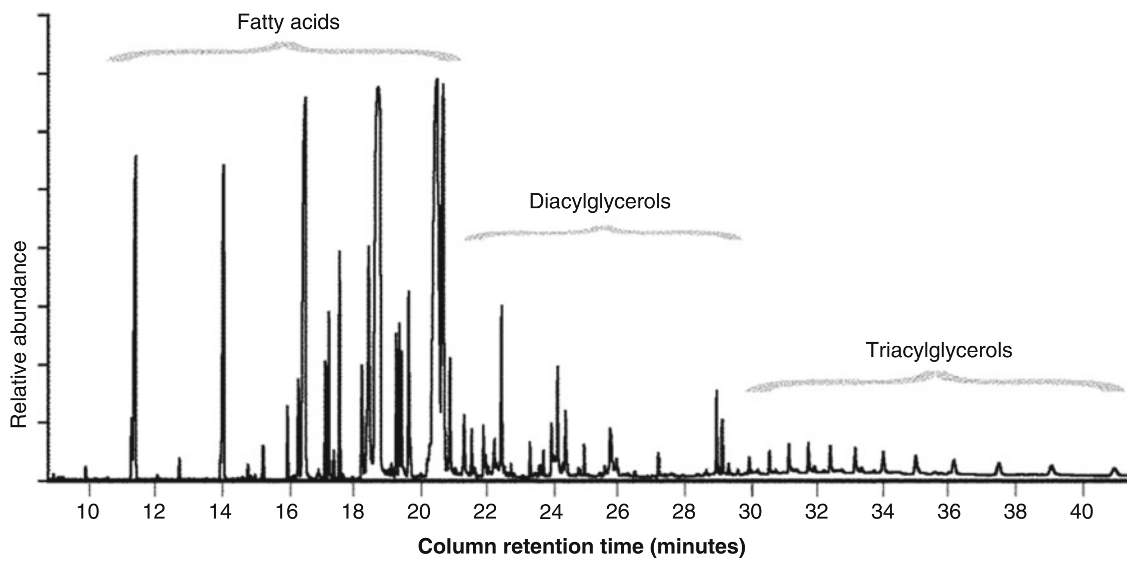
Many different laboratory-based recovery protocols and wet-chemistry and instrumental analytical techniques have been used in subsequent attempts to identify the diverse range of fats, oils, proteins, starches, alcohols, resins, waxes, and pigments that may survive in archaeological materials – many with ambiguous or misleading results (Jones, 2001; Pollard et al., 2007; Evershed, 2008; Gregg, 2010). Advances in computer technology and analytical instrumentation in the late 1970s have resulted in a more systematic approach to the classification of organic compounds in many disciplines within the natural sciences. An overview of the basic tenets of analytical chemistry and a comprehensive examination of the major recovery protocols and instrumental analytical techniques and their application to archaeology can be found in Pollard et al. (2007). Brief summaries of the principal methods used in examining different classes of organic matter are provided here, but due to the preferential survival of lipids in ceramics recovered from many archaeological contexts and limited availability of space in this entry, greater emphasis will be placed on explanation of those recovery protocols and instrumental analytical techniques that have proven highly successful in the identification of animal fats, vegetable oils, plant resins, waxes, and bitumen from pottery. The summary of the principal techniques used in gas chromatography and mass spectrometry provided below will inform the subsequent discussion on the degradation processes affecting the differential preservation of lipids at archaeological sites, in addition to later sections dealing with the survival of residues of sugars, starches, proteins, amino acids, and DNA at archaeological sites.

Principles of gas chromatography and mass spectrometry

Gas chromatography (GC) separates and measures the molecules in a compound on the basis of their physical behavior. Gases, liquids, and solids can all be separated on a GC column, but before organic residues from archaeological sites can be analyzed, these preserved compounds must be released from the matrix of materials within which they are bound. This can accomplished through a variety of recovery protocols that will be discussed below. All compounds are introduced into the GC column dissolved in an organic solvent solution (such as hexane or dichloromethane) that is vaporized as it is injected into a carrier gas (such as hydrogen or helium); this is known as the mobile phase (Figure 1). The carrier gas then passes the components of the vaporized solution into a long, coiled, silica-lined, narrow-diameter, metal column inside a temperature-controlled oven where organic compounds 'stick' in what is known as the stationary phase. Temperatures are programmed to rise in the oven at very controlled rates, and compounds are released, or eluted, into the carrier gas again as temperatures rise and their volatility increases. The retention times, elution orders, and relative abundances of the different molecules in the compound are then measured and recorded as they are released and combusted in a device known as a flame ionization detector. Components with lower molecular weights sharing electrons between atoms equally elute before those with higher weights sharing electrons unequally, and thus they are retained in the column for longer periods (Pollard et al., 2007). The retention times, elution orders, and



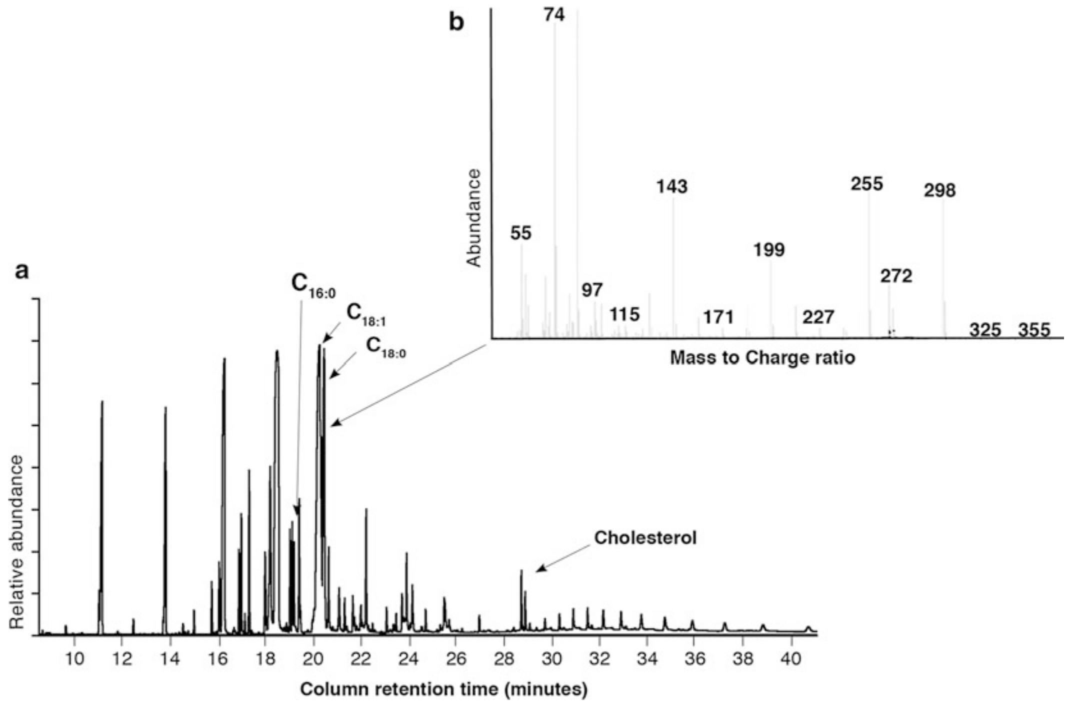
Organic Residues, Figure 1 Schematic diagram of a gas chromatography column.



Organic Residues, Figure 2 A chromatogram of the molecular components of a modern butter fat sample. The retention times, elution orders, and relative abundances of different molecular components in an unknown archaeological sample can be matched to those of known modern organic substances. Molecular components are released in a predictable sequence by the GC column based on their individual boiling points, with shorter carbon chain fatty acids eluting before diacylglycerols and triacylglycerols.

relative abundances of molecules in the unknown samples are then compared to those of known compounds, generally through the use of a chromatogram, which is a graphic representation of the measured values of molecular components in the separated organic compound (Figure 2).

A mass spectrometer is often coupled to the output port of a GC in order to match the molecular weights and ion fragments of the components in a compound. As molecules are released from the gas chromatography column, the mass spectrometer generates a shower of high-energy electrons that removes an electron from each molecule, and creates a stream of charged particles that is subsequently bent by a powerful magnetic or electrical field. The positive molecular ions in the stream of charged particles are separated from one another on the basis of their atomic masses (Pollard et al., 2007), with lighter ion fragments bending more readily than ions having heavier masses. The ion fragments of individual molecular components of a potsherd extract can then be statistically



Organic Residues, Figure 3 Molecular weights and ion fragments of individual molecular components in organic substances recovered from archaeological sites can be measured and matched to those of known compounds through the use of a computer database attached to a mass spectrometer. (**a**) Gas chromatogram of all lipids making up a modern butter fat sample. (**b**) Mass spectra of a singular molecular component ($C_{18:0}$ saturated fatty acid) that has been isolated from all other components of the modern butter fat sample.

matched to those of known organic and inorganic compounds through an attached computer database (Figure 3). Different compounds often share many similar molecular components that vary only to a small degree, and therefore, mass spectrometry provides corroboration for the identification of compounds by gas chromatography, and it offers increased efficiency and reliability in the identification of complex mixtures.

Molecular characterization of animal fats, vegetable oils, plant resins, waxes, and bitumen using gas chromatography (GC) and mass spectrometry (MS)

Two pioneering examinations of archaeological residues using gas chromatography and mass spectrometry were conducted on substances surviving in Gallo-Roman pottery (Condamin et al., 1976; Rottländer and Hartke, 1982), but much like the earlier work of Berthelot, results of these studies were ambiguous because they relied solely on fatty acid distributions for the classification of residues and their assignment to specific plant and animal species. Concentrations of $C_{16:0}$ and $C_{18:0}$ saturated fatty acids can, in fact, be useful in distinguishing whether archaeological residues are of plant or animal origin, but these are of little diagnostic value by themselves in differentiating major classes of mammalian fats or plant species (Heron and Evershed, 1995, 260). Working with a "resinous adhesive material" that had been recovered from a third century BCE Carthaginian shipwreck off the coast of Sicily, National Gallery of Britain conservators John Mills and Raymond White were the first researchers to identify an archaeologically retrieved organic substance with certainty by matching chromatographic elution orders and abundances of a unique molecular biomarker (diterpenoid methyl esters) found in pine tree resins (Mills and White, 1977).

A number of research studies conducted in the early 1990s by Richard Evershed, Carl Heron and colleagues in the Department of Chemistry at the University of Liverpool set the agenda for methods used in recovery and analysis of lipids from archaeological materials up until the present day (Evershed et al., 1990, 1992; Heron et al., 1991, 1994). Evershed and Heron developed a protocol for the extraction of residues from the clay matrix of archaeological pottery fragments in which a fine ceramic powder was removed from the interior surface with a high-speed modeling drill and collected on sterile sheets of household aluminum foil under controlled laboratory conditions. Lipids were subsequently extracted from the ceramic powder through repeated applications of a solution of chloroform and methanol solvents in a glass vial while being subjected to high frequency sound waves to free organic compounds bound within the ceramic matrix. Solvent solutions were then concentrated and the major classes of lipids (saturated and unsaturated fatty acids, monoacylglycerols, diacylglycerols, and triacylglycerols) separated from one another through gas chromatography (GC) as outlined above. The relative abundances, elution orders, and retention times of these specific lipid classes were then measured and compared with modern reference samples (Evershed et al., 1990, 1992; Heron et al., 1991, 1994). This research group successfully identified molecular compounds surviving in pottery from three very different archaeological contexts in Great Britain: (1) small amounts of cholesterol confirmed the presence of animal fats in vessels recovered from a Roman villa (Heron et al., 1991); (2) lipids known from leafy vegetables indicated the cooking of cabbage at a medieval Saxon hamlet (Evershed et al., 1991); and (3) other long-chain carbon compounds from beeswax attested to the collection of honey (if not the keeping of bees) during the late Neolithic period in northern Europe (Heron et al., 1994).

Since the early 1990s, many researchers throughout the world have built on Evershed's and Heron's early work (including members of their respective research groups at the University of Bristol and the University of Bradford) to develop yet further protocols that could maximize the recovery of lipids from both pottery and archaeological sediments. Comparisons of methods using a range of different organic solvents as well as acidification and saponification techniques can be found in Stern et al. (2000) and Gregg (2010).

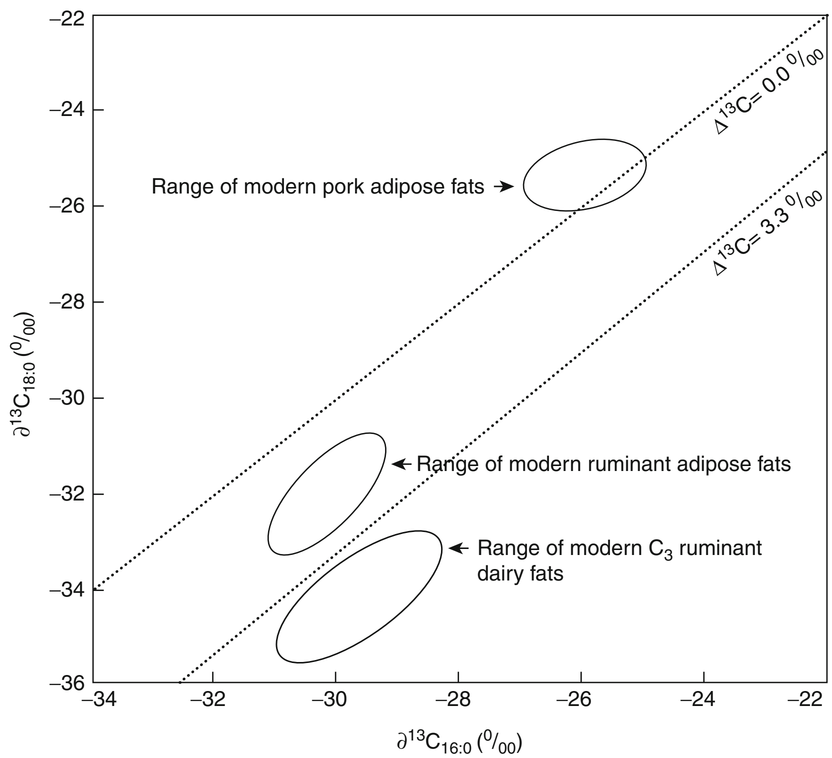
Although many of these techniques have proven successful in the recovery and identification of organic residues from different archaeological contexts in many regions, 20 years of intensive research have shown that unique molecular biomarkers or diagnostic distributions of longer carbon chain compounds are rarely preserved at archaeological sites for more than 2 or 3,000 years (Heron et al., 1994; Boëda et al., 1996; Connan et al., 2004; Mirabaud et al., 2007; Gregg et al., 2007). It is suspected that the delayed decomposition of lipids within archaeological pottery is due to their being absorbed into the clay fabric of vessels (Evershed et al., 1990; Heron et al., 1991), but diagnostic long carbon chain molecules survive only under exceptional circumstances, such as the anaerobic conditions at the submerged fourth millennium BCE site at Clairvaux XIV in the French Jura (Mirabaud et al., 2007) or the continuously desiccated 18th dynasty Egyptian capital at Amarna (Stern et al., 2000). Bitumen appears to be the one notable exception, with extant molecular signatures having been identified in pottery vessels from 8th millennium BCE sites in southern Mesopotamia (Connan et al., 2004; Gregg et al., 2007) and on the surface of 40,000-year-old Middle Paleolithic tools from northern Syria (Boëda et al., 1996).

Robert White's *Principles and Practice of Soil Science* (2006) provides a useful guide to the physical and chemical process involved in biodegradation of organic compounds under different soil and climatic conditions. Colonizing insects, arthropods, annelids, fungi, and bacteria can all affect the survival of buried organic matter, but microbial degradation is accelerated in most depositional environments through increases in temperature, moisture, and hydrolysis resulting from the acidic or alkaline conditions of the soil (White, 2006; Pollard et al., 2007). However, it is the differences in the physical characteristics of the molecular components in a substance that results in the preferential preservation of some lipids more so than others (Eglinton and Logan, 1991; Pollard et al., 2007). Hydrophobic classes of lipids that share electrons between atoms symmetrically, such as nonpolar $C_{16:0}$ and $C_{18:0}$ saturated fatty acids in animal fats and vegetable oils and long carbon chain compounds in bitumen, waxes, and tree resins, are much more likely to survive microbial degradation during burial for prolonged periods of time than water-soluble lipid species that share electrons between atoms asymmetrically (Eglinton and Logan, 1991; Heron et al., 1994; Heron and Evershed, 1995; Connan, 1999).

Isotopic characterization of $C_{16:0}$ and $C_{18:0}$ fatty acids from remnant animal fats and vegetable oils

As a result of poor preservation of distinctive molecular biomarkers in the overwhelming majority of pottery fragments from Iron Age, Bronze Age, and Neolithic sites in Europe, a group led by Evershed established new criteria for identification of animal fats by specifically targeting saturated fatty acids that were preserved in archaeological ceramics (Evershed et al., 1997). Employing gas chromatography and combustion isotope ratio mass spectrometry (GC-C-IRMS) as analytical techniques, Evershed and his colleagues measured the stable carbon composition ($^{13}C/^{12}C$) of modern animal fats and observed that $\delta^{13}C$ values of $C_{16:0}$ and $C_{18:0}$ fatty acids from ruminant animals (sheep, goats, and cattle), pigs, and dairy foods fell into discrete ranges that could be used to categorize the biological origins of residues from archaeological materials. The basis for identification of fatty acids recovered from archaeological pottery is illustrated in Figure 4. Ratios of $\delta^{13}C$ values plotting below the $\Delta^{13}C = -3.3$ line are categorized as dairy fats; values plotting between the $\Delta^{13}C = -3.3$ and $\Delta^{13}C = 0$ lines are categorized as ruminant carcass fats; and values plotting above $\Delta^{13}C = 0$ line are categorized as pig fats. By convention, the lower case letter delta in the Greek alphabet (δ) is used to denote small – parts per thousand (per mil or ‰) – differences in isotopic composition of carbon ($^{13}C/^{12}C$) in the fatty acids, while the uppercase letter delta in the Greek alphabet (Δ) is used to denote subsequent comparison of δ values of individual fatty acids to one another.

These advances have opened new windows for investigation of subsistence practices associated with different prehistoric cultural traditions. A number of notable studies have used these criteria as evidence for the processing or consumption of dairy products at Medieval to Neolithic



Organic Residues, Figure 4 Ratios of δ^{13}C values of $C_{16:0}$ and $C_{18:0}$ fatty acids used to categorize dairy fats, ruminant carcass fats, and pig fats.

period sites (Dudd and Evershed, 1998; Copley et al., 2003; Craig et al., 2005; Spangenberg et al., 2006; Gregg et al., 2009; Dunne et al., 2012; Salque et al., 2013), with the earliest date for milk use currently linked to cattle herding in the Near East and southeastern Europe (Evershed et al., 2008). Other studies have characterized the isotopic composition of additional modern reference materials and used this technique to identify fatty acids from a wide range of archaeological contexts, including plant oils and animal fats used as fuel in ceramic lamps in Bronze Age Egypt (Copley et al., 2005), marine mammal blubber in slab-lined pits in prehistoric Norway (Heron et al., 2009), and the milking of horses into pottery vessels shortly after their initial domestication on the steppes of Central Asia (Outram et al., 2009). However, there also remains the potential for the reporting of false or ambiguous results given our current state of knowledge of modern biological processes and diagenetic factors affecting the isotopic composition of remnant plant oils and animal fats (Gregg et al., 2009; Gregg and Slater, 2010; Steele et al., 2010). Studies by a number of research groups (Spangenberg et al., 2006; Gregg et al., 2009; Gregg and Slater, 2010; Steele et al., 2010) have shown that there is greater diversity in the fractionation of carbon isotopes (the division of carbon into relative amounts of ^{13}C and ^{12}C) than previously reported using the criteria established by Evershed et al. (1997).

Variations in the fractionation of carbon isotopes in plants having different photosynthetic pathways produce a shift in the δ^{13}C values of fatty acids in animals that consume them (O'Leary, 1981; Lee-Thorp 2008), thus reinforcing the fact that you are what you eat. Animals that exclusively consume δ^{13}C grasses or cereals in regions with temperate climates, such as Europe, have more negative δ^{13}C values than animals consuming large quantities of C_4 plants, such as corn, sorghum, and millet, or tropical grasses or chenopods that are abundant in many other parts of the world (O'Leary, 1981). Researchers in the Evershed group had initially suggested that isotopic values falling between the discrete modern ranges in Figure 4 could be attributed to the mixing of animal fats in antiquity (Dudd and Evershed, 1998, 1480), but more recent observations of the isotopic composition of modern olive oils by Steele et al. (2010, 3484) demonstrate that interpretations of δ^{13}C values falling between these ranges as mixtures of animal fats "can no longer be considered valid." Isotopic values of modern carcass fats and dairy foods from central Europe (Spangenberg et al., 2006) and the Middle East (Gregg et al., 2009; Gregg and Slater, 2010) have also been observed to plot outside the currently applied ranges that were generated based on modern samples from the United Kingdom (Dudd and Evershed, 1998; Copley et al., 2003). Given the complexities of differentiating the isotopic values of plant oils from animal fats, it is essential not only to determine the extent to which stable carbon values of animal fats and dairy foods are affected by the photosynthetic pathway of vegetation that animals are consuming, but also to compare the isotopic composition of ancient residues with the full suite of plant and animal species that may have been consumed within the region or ancient period of interest (Gregg, 2010; Greenfield, 2010).

Sugars and starches

Sugars are simple carbohydrates (monosaccharides and disaccharides) found in an extensive range of foodstuffs, whereas starches are the semicrystalline structures (polysaccharides) that hold large numbers of sugars together to act as the main energy store in green plants. Both sugars and starches are highly polar organic substances with molecular bonds that are readily dissolved in water (McMurry, 2004; Pollard et al., 2007). Researchers have long been interested in differentiating the physical characteristics of starches by genera and species (Reichert, 1913), and many studies have used microscopic examination of the morphological attributes of starch grains recovered from archaeological sediments as evidence for subsistence practices of prehistoric populations (Samuel, 1996; Piperno and Holst, 1998; Piperno et al., 2000; Piperno et al., 2004; Henry and Piperno, 2008; Mercader et al., 2008; Hardy et al., 2009; Piperno et al., 2009). However, many other researchers have also questioned whether these complex carbohydrates are able to survive burial for prolonged periods as discrete entities while still retaining their diagnostic potential in reconstructing ancient human diets (Atchinson and Fullagar, 1998; Perry, 2001; Haslam, 2004; Reber and Evershed, 2004a; Evershed, 2008), with Wilson et al. (2010, 594) recently noting that "how variations in [starch granule] shape occur, the effects of local geographical and environmental effects on granule shape and the diagenetic effects of aging are not fully understood or explained."

Attempts to identify fruit sugars and starchy grains from archaeological contexts through chemical analysis also have not proven to be particularly successful (Reber and Evershed, 2004a; Evershed, 2008). Michael Haslam points out that "once a component such as starch has entered the soil and begun to be broken down, it is rarely possible to determine just how much was present, owing to biochemical similarities in the make-up of all living things" (Haslam, 2004, 1720). The poor preservation of complex carbohydrates under most soil conditions is further aggravated by the lack of any known species-specific lipid biomarkers for starch grains (Reber and Evershed, 2004a), and the masking of starch lipids by those from other foods such as meat, milk, fish, and oily seeds (Reber and Evershed, 2004a). Reber and Evershed (2004a, 400) note that this masking often "leads to the underestimation of starchy staple lipids present in a residue," making it difficult, if not impossible, to confirm evidence of starchy grains through molecular criteria alone. However, Reber and Evershed (2004b) have been able to demonstrate a chronological progression of the processing of maize in pottery vessels during the early Mississippian period in southern North America, ca. 800–1,100 cal AD. Through the adaptation of the GC-MS and GC-IRMS instrumental analytical techniques described above, Reber and Evershed (2004b) characterized the isotopic values of long-chain carbon compounds surviving in potsherds recovered from precontact sites along the Mississippi Valley. Isotopic analysis revealed a change in $\delta^{13}C$ values of these molecular compounds coinciding with botanical evidence for the introduction of maize, a C_4 plant, into the American Bottom region from the Lower Mississippi Valley between 1,000 and 1,100 cal AD (Reber and Evershed, 2004b).

Patrick McGovern of the University of Pennsylvania's Museum of Archaeology and Anthropology has directed projects specifically targeting trace elements in pottery vessels associated with the conversion of sugars and starches to alcohol; the presence of these elements can then be used as evidence of winemaking and brewing during prehistoric periods and regions. McGovern and his colleagues have reported finding direct chemical evidence of the manufacture or storage of alcoholic beverages in pottery vessels from the Middle East, China, and Central America (Michel et al., 1992, 1993; McGovern et al., 1996, 1997, 2004; Cavalieri et al., 2003; Henderson et al., 2007). A number of researchers have questioned the reliability of the Fourier transform infrared spectroscopy (FTIR) and wet chemistry "spot tests" used in the studies from the ancient Middle East (Boulton and Heron, 2000; Guasch-Jané et al., 2004; Pollard et al., 2007; Stern et al., 2008) and identification of trace amounts of beeswax associated with honey in "mixed fermented beverage" from the Early Neolithic period in China (Evershed, 2008). There also remains uncertainty as to whether the biomarkers calcium oxalate and tartaric acid recovered from potsherd extracts in McGovern's studies can be, respectively, interpreted as unambiguous evidence that the vessels ever contained beer or wine rather than other plant foods or fruit-based beverages (Hornsey, 2003; Stern et al., 2008; Evershed, 2008; Gregg, 2010). In a recent study attempting to uncover chemical evidence for wine production in the ancient Near East, Hans Barnard and colleagues (2011) built on McGovern's pioneering work and identified the presence of malvidin (a plant pigment that provides both pomegranates and grapes with their red color) in two Late Chalcolithic period potsherds from the Areni-1 cave complex in Armenia. Barnard et al. (2011) conservatively note that the presence of malvidin is not necessarily associated with ancient wine production but can only be used as evidence of the presence of grapes or pomegranates, both species native to the region.

Proteins, amino acids, and DNA

The overwhelming majority of studies examining extant organic residues have focused on the identification of molecular and isotopic biomarkers of lipids rather than proteins, due to the apparent preferential survival of animal fats and vegetable oils in most archaeological contexts. However, when proteins are preserved, they can provide species-specific identification of organic residues through the use of a wide range of immunological testing methods (Smith and Wilson, 1992, 2001; Newman et al., 1993; Barnard and Eerkens, 2007; Stevens et al., 2010). But many researchers have questioned the merit of attempting to characterize proteins that may survive in organic residues. The peptide bonds holding long chains of amino acids together break down rapidly under highly acidic or alkaline soil conditions, and concentrations are often below the detectable limits of conventional chromatography biomarker techniques (Evershed and Tuross, 1996).

Uncertainties concerning the diagnostic potential of proteins in archaeological materials have been aggravated by the controversy surrounding the detection of blood residues on the surfaces of prehistoric stone tools and alleged identification of species (Loy, 1983; Loy and Wood, 1989; Loy and Hardy, 1992). Material scientists, biochemists, immunologists, and archaeologists (Custer et al., 1988; Gurfinkel and Franklin, 1988; Smith and Wilson, 1992, 2001; Manning, 1994; Downs and Lowenstein, 1995; Gernaey et al., 2001; Pollard et al., 2007; Heaton et al., 2009) have all questioned the validity of the discovery of hemoglobin on stone tools based on the use of chemical test strips for the detection of hemoglobin in urine (Loy, 1983; Loy and Wood, 1989) or the visual recognition of crystalline structure of salts allegedly formed through the precipitation of proteins from a solution in which the tools were soaked (Loy, 1983; Loy and Wood, 1989; Loy and Hardy, 1992). The selectivity of chemical test strips is limited to hemoglobin, with consistent false-positive results produced through the presence of many organic compounds present in archaeological soils (Custer et al., 1988; Manning, 1994; Downs and Lowenstein, 1995). Researchers have also not been able to replicate the crystalline structures allegedly attesting to the presence of hemoglobin using the methods described by Loy and colleagues (Smith and Wilson, 2001).

Despite the improbabilities associated with the identification of proteins in archaeological residues, University of Newcastle researchers Matthew Collins and Oliver Craig did have some initial success in identifying bovine aS1-casein from cow's milk in storage vessels from an Iron Age site in the Hebrides through the use of a hydrofluoric acid digestion-and-capture immunoassay (DACIA) method (Craig and Collins, 2000; Craig et al., 2000). However, these researchers were unable to replicate their results in examination of pottery fragments of much greater antiquity from three Neolithic sites in the Danube basin (Craig et al., 2005), and subsequently they abandoned the DACIA process and adopted the lipid recovery protocols and GC-C-IRMS techniques outlined above.

Recent innovations in electrospray ionization mass spectrometry (ESI-MS) may allow archaeological researchers to resolve molecular structures of both fats and proteins preserved in archaeological residues that have not thus far been possible to characterize through conventional gas chromatography and mass spectrometry techniques (Mirabaud et al., 2007; Solazzo et al., 2008; Stevens et al., 2010). In electrospray ionization mass spectrometry, a small amount of the substances being analyzed is dissolved in a volatile mixture of solvents and introduced into a chamber where a charged field at the tip of a hypodermic needle disperses the mixture into a fine spray of charged droplets (Fenn et al., 1990; Pramanik et al., 2002). The volatile solvents rapidly evaporate through a sequence of small Coulomb explosions, with individual ions from the substance being released into the ambient gas of the chamber before being sent to a mass analyzer (Fenn et al., 1990). Electrospray instrumental methods are particularly well suited to the analysis of fats and proteins because they compensate for the tendency of macromolecules such as diagnostic triacylglycerides in animal fats and amino acids in proteins to fractionate when they are ionized (Pramanik et al., 2002).

Mirabaud et al. (2007) used ESI-MS to obtain higher resolution in molecular distributions of triacylglycerides from carcass fats and dairy foods of modern ruminant animals than had been previously possible through conventional GC-MS techniques. Triacylglyceride distributions of ruminant carcass fats and dairy foods become indistinguishable from one another following burial for prolonged periods of time (Heron and Evershed, 1995), but Mirabaud et al. (2007) were able to match triacylglyceride distributions of milk fats from modern European cattle to those of potsherd extracts from a long submerged Neolithic settlement at Clairvaux XIV in France. French and American researchers also used ESI-MS to identify protein peptide sequences of seal muscle and whale blubber in the clay matrix of an 800-year-old Inupiat potsherd from Point Barrow in northern Alaska through comparison with modern reference samples using a protein-matching database (Solazzo et al., 2008). While electrospray ionization mass spectrometry could prove useful in identifying organic compounds in archaeological residues recovered from anaerobic burial environments or those that have remained frozen for prolonged periods, this instrumental technique may have little applicability in characterizing organic residues from the vast majority of archaeological sites. Much like mammoths from northern Siberia (Michel, 1998), the "Iceman" from the Italian Alps (Gostner and Egarter Vigl, 2002), or "bog bodies" from the northern Europe (Stankiewicz et al., 1997), frigid or anaerobic conditions have likely protected molecular structures of fats and proteins from the kinds of biodegradation processes that prevail at archaeological sites throughout of the rest of the world.

This is also much the same case with ancient DNA. The underlying mechanisms of DNA degradation are becoming increasingly well understood (Collins et al., 2002; Götherström et al., 2002; Schwarz et al., 2009; Adler et al., 2011), and reviews of the physiological and diagenetic processes affecting the survival and recovery of DNA from teeth and bone can be found in Collins et al. (2002) and Adler et al. (2011). The external sugar-phosphate backbones of DNA molecules are made up of water-soluble ribose sugars and phosphates that are highly susceptible to biodegradation processes, whereas the internal nitrogenous bases making up the genetic replication sequences in DNA (adenine, guanine, thymine, and cytosine) are water resistant and therefore more likely to survive. Götherström et al. (2002) have shown that DNA is absorbed into the crystalline structure of the mineral portion of bone and stabilized by hydroxyapatite in calcified tissue and collagen. However, only a limited number of studies inform our understanding of the factors affecting its preservation in organic residues from archaeological sites (Hansson and Foley, 2008; Foley et al., 2012). Maria Hansson and Brendan Foley (2008) have extracted fragmentary strands of olive, oregano, and *Pistacia lentiscus* DNA from scrapings of the interior surfaces of two amphorae from a 2,400 year-old shipwreck off the Greek island of Chios using polymerase amplification techniques and existing criteria established for authenticating ancient DNA. The survival of DNA shows that a wide range of foodstuffs were shipped in these vessels, and it allowed these researchers to question long-standing assumptions about the use of amphorae as exclusively wine and olive oil transport containers in ancient Greece (Foley et al., 2012). However, the low water solubility of olive oil, which is suspected to have been shipped in these vessels on multiple occasions, and the relatively anaerobic conditions of the deepwater location from which they were recovered would both have aided in the preservation of the DNA of other substances shipped in the same containers (Hansson and Foley, 2008).

Summary

Chemical analysis of organic residues is becoming an increasingly useful tool in identifying economic activities and subsistence practices associated with different cultural traditions or archaeological time periods in both the Old and the New Worlds. Due to variable rates of degradation in individual components of organic compounds, however, unambiguous identification of amorphous or invisible residues surviving at archaeological sites is not always a straightforward task. Interpretations of chemical data must be evaluated in the context of complementary or contradictory lines of evidence that inform the researchers' understanding of the problems they are hoping to clarify. It might not be practicable for archaeologists to extract residues and conduct analyses themselves, but both archaeologists and the natural scientists with whom they collaborate need to be aware of all of the constraints placed on classification of organic substances by degradation processes at archaeological sites. And both sides must be confident that molecular or isotopic biomarkers are unique to a specific organism or physiological process before being used as evidence of past human activity.

Bibliography

Adler, C. J., Haak, W., Donlon, D., and Cooper, A., 2011. Survival and recovery of DNA from ancient teeth and bones. *Journal of Archaeological Science*, **38**(5), 956–964.

Atchinson, J., and Fullagar, R., 1998. Starch residues on pounding elements from Jinmium rock-shelter. In Fullagar, R. (ed.), *A Closer Look: Recent Australian Studies of Stone Tools*. Sydney: School of Archaeology, University of Sydney, Australia. Sydney University Archaeological Methods, Vol. 6, pp. 109–125.

Barnard, H., and Eerkens, J. W., 2007. *Theory and Practice of Archaeological Residue Analysis*. Oxford: Archaeopress. British Archaeological Reports International Series, Vol. 1650.

Barnard, H., Dooley, A. N., Areshian, G., Gasparyan, B., and Faull, K. F., 2011. Chemical evidence for wine production around 4000 BCE in the Late Chalcolithic Near Eastern highlands. *Journal of Archaeological Science*, **38**(5), 977–984.

Berthelot, M., 1906. A. Liquides provenant d'un flacon trouvé près de Reims. Archéologie et Histoire des Sciences. *Mémoires de l'Académie des Sciences de l'Institut Paris IIe série*, **49**, 128–131.

Boëda, E., Connan, J., Dessort, D., Muhesen, S., Mercier, N., Valladas, H., and Tisnérat, N., 1996. Bitumen as a hafting material on Middle Palaeolithic artefacts. *Nature*, **380**(6572), 336–338.

Boulton, N., and Heron, C., 2000. Chemical detection of ancient wine. In Murray, M. A., Viticulture and Wine Production. In Nicholson, P. T., and Shaw, I. (eds.), *Ancient Egyptian Materials and Technology*. Cambridge: Cambridge University Press, pp. 599–603.

Brongniart, A., 1844. *Traité des arts céramiques, ou des poteries, considérées dans leur histoire, leur pratique et leur théorie*. Paris: Béchet jeune.

Caley, E. R., 1951. Early history and literature of archaeological chemistry. *Journal of Chemical Education*, **28**(2), 64–66.

Caley, E. R., 1967. Early history of chemistry in the service of archaeology. *Journal of Chemical Education*, **44**(3), 120–123.

Cavalieri, D., McGovern, P. E., Hartl, D. L., Mortimer, R., and Polsinelli, M., 2003. Evidence for *S. cerevisiae* fermentation in ancient wine. *Journal of Molecular Evolution*, **57**(Suppl. 1), S226–S232.

Collins, M. J., Nielsen-Marsh, C. M., Hiller, J., Smith, C. I., Roberts, J. P., Prigodich, R. V., Wess, T. J., Csapò, J., Millard, A. R., and Turner-Walker, G., 2002. The survival of organic matter in bone: a review. *Archaeometry*, **44**(3), 383–394.

Condamin, J., Formenti, F., Metais, M. O., Michel, M., and Blond, P., 1976. The application of gas chromatography to the tracing of oil in ancient amphorae. *Archaeometry*, **18**(2), 195–201.

Connan, J., 1999. Use and trade of bitumen in antiquity and prehistory: molecular archaeology reveals secrets of past civilizations. *Philosophical Transactions of the Royal Society of London, Series B: Biological Sciences*, **354**(1379), 33–50.

Connan, J., Nieuwenhuyse, O. P., Van As, A., and Jacobs, L., 2004. Bitumen in early ceramic art: bitumen-painted ceramics from Late Neolithic Sabi Abyad (Syria). *Archaeometry*, **46**(1), 115–124.

Copley, M. S., Bertan, R., Dudd, S. N., Docherty, G., Mukherjee, A. J., Straker, V., Payne, S., and Evershed, R. P., 2003. Direct chemical evidence for widespread dairying in prehistoric Britain. *Proceedings of the National Academy of Sciences*, **100**(4), 1524–1529.

Copley, M. S., Bland, H. A., Rose, P., Horton, M., and Evershed, R. P., 2005. Gas chromatographic, mass spectrometric and stable carbon isotopic investigations of organic residues of plant oils and animal fats employed as illuminants in archaeological lamps from Egypt. *Analyst*, **130**(6), 860–871.

Craig, O. E., and Collins, M. J., 2000. An improved method for immunological detection of mineral bound protein using hydrofluoric acid and direct capture. *Journal of Immunological Methods*, **236**(1–2), 89–97.

Craig, O. E., Mulville, J., Parker-Pearson, M., Sokol, R., Gelsthorpe, K., Stacey, R., and Collins, M., 2000. Detecting milk proteins in ancient pots. *Nature*, **408**(6810), 312.

Craig, O. E., Chapman, J., Heron, C., Willis, L. H., Bartosiewicz, L., Taylor, G., Whittle, A., and Collins, M., 2005. Did the first farmers of central and eastern Europe produce dairy foods? *Antiquity*, **79**(306), 882–894.

Custer, J. F., Ilgenfritz, J., and Doms, K. R., 1988. A cautionary note on the use of chemstrips for detection of blood residues on prehistoric tools. *Journal of Archaeological Science*, **15**(3), 343–345.

Downs, E. F., and Lowenstein, J. M., 1995. Identification of archaeological blood proteins: a cautionary note. *Journal of Archaeological Science*, **22**(1), 11–16.

Dudd, S. N., and Evershed, R. P., 1998. Direct demonstration of milk as an element of archaeological economies. *Science*, **282**(5393), 1478–1481.

Dunne, J., Evershed, R. P., Salque, M., Cramp, L., Bruni, S., Ryan, K., Biagetti, S., and di Lernia, S., 2012. First dairying in green Saharan Africa in the fifth millennium BC. *Nature*, **486**(7403), 390–394.

Eglinton, G., and Logan, G. A., 1991. Molecular preservation. *Philosophical Transactions of the Royal Society of London, Series B: Biological Sciences*, **333**(1268), 315–327.

Evershed, R. P., 2008. Organic residue analysis in archaeology: the archaeological biomarker revolution. *Archaeometry*, **50**(6), 895–924.

Evershed, R. P., and Tuross, N., 1996. Proteinaceous material from potsherds and associated soils. *Journal of Archaeological Science*, **23**(3), 429–436.

Evershed, R. P., Heron, C., and Goad, L. J., 1990. Analysis of organic residues of archaeological origin by high temperature gas chromatography-mass spectrometry. *Analyst*, **115**(10), 1339–1342.

Evershed, R. P., Heron, C., and Goad, L. J., 1991. Epicuticular wax components preserved in pot sherds as chemical indicators of leafy vegetables in ancient diets. *Antiquity*, **65**(248), 540–544.

Evershed, R. P., Heron, C., Charters, C., and Goad, L. J., 1992. Chemical analysis of organic residues in ancient pottery: methodological guidelines and applications. In White, R., and Page, H. (eds.), *Organic Residues in Archaeology: Their Identification and Analysis*. London: United Kingdom Institute for Conservation, Archaeology Section, pp. 11–25.

Evershed, R. P., Mottram, H. R., Dudd, S. N., Charters, S., Stott, A. W., Lawrence, G. J., Gibson, A. M., Conner, A., Blinkhorn, P. W., and Reeves, V., 1997. New criteria for the identification of animal fats preserved in archaeological pottery. *Naturwissenschaften*, **84**(9), 402–406.

Evershed, R. P., Payne, S., Sherratt, A. G., Copley, M. S., Coolidge, J., Urem-Kotsu, D., Kotsakis, K., Özdoğan, M., Özdoğan, A. E., Nieuwenhuyse, O., Akkermans, P. M. M. G., Bailey, D., Andeescu, R.-R., Campbell, S., Farid, S., Hodder, I., Yalman, N., Özbaşaran, M., Bıçakcı, E., Garfinkel, Y., Levy, T., and Burton, M. M., 2008. Earliest date for milk use in the Near East and southeastern Europe linked to cattle herding. *Nature*, **455**(7212), 528–531.

Fenn, J. B., Mann, M., Meng, C. K., Wong, S. F., and Whitehouse, C. M., 1990. Electrospray ionization – principles and practice. *Mass Spectrometry Reviews*, **9**(1), 37–70.

Foley, B. P., Hansson, M. C., Kourkoumelis, D. P., and Theodoulou, T. A., 2012. Aspects of ancient Greek trade re-evaluated with amphora DNA evidence. *Journal of Archaeological Science*, **39**(2), 389–398.

Forbes, R. J., 1936. Note on a lump of asphalt from Ur. *Journal of the Institute Petroleum Technology*, **XXII**, 180.

Gernaey, A. M., Waite, E. R., Collins, M. J., and Craig, O. E., 2001. Survival and interpretation of archaeological proteins. In Brothwell, D. R., and Pollard, A. M. (eds.), *Handbook of Archaeological Sciences*. Chichester: Wiley, pp. 323–329.

Gostner, P., and Egarter Vigl, E., 2002. Report of radiological-forensic findings on the Iceman. *Journal of Archaeological Science*, **29**(3), 323–326.

Götherström, A., Collins, M. J., Angerbjörn, A., and Lidén, K., 2002. Bone preservation and DNA amplification. *Archaeometry*, **44**(3), 395–404.

Greenfield, H. J., 2010. The secondary products revolution: the past, the present and the future. *World Archaeology*, **42**(1), 29–54.

Gregg, M. W., 2010. *Organic Residue Analysis and the First Uses of Pottery in the Ancient Middle East*. Oxford: John and Erica Hedges Limited. British Archaeological Reports, International Series, Vol. 2065.

Gregg, M. W., and Slater, G. F., 2010. A new method for extraction, isolation and transesterification of free fatty acids from archaeological pottery. *Archaeometry*, **52**(5), 833–854.

Gregg, M. W., Brettell, R., and Stern, B., 2007. Bitumen in Neolithic Iran: biomolecular and isotopic evidence. In Glascock, M. D., Speakman, R. J., and Popelka-Filcoff, R. S. (eds.), *Archaeological Chemistry: Analytical Methods and Archaeological Interpretation*. Washington, DC: American Chemical Society, pp. 137–151.

Gregg, M. W., Banning, E. B., Gibbs, K., and Slater, G. F., 2009. Subsistence practices and pottery use in Neolithic Jordan: molecular and isotopic evidence. *Journal of Archaeological Science*, **36**(4), 937–946.

Guasch-Jané, M. R., Ibern-Gómez, M., Andrés-Lacueva, C., Jáuregui, O., and Lamuela-Raventós, R. M., 2004. Liquid chromatography with mass spectrometry in tandem mode applied for the identification of wine markers in residues from ancient Egyptian vessels. *Analytical Chemistry*, **76**(6), 1672–1677.

Gurfinkel, D. M., and Franklin, U. M., 1988. A study of the feasibility of detecting blood residue on artifacts. *Journal of Archaeological Science*, **15**(1), 83–97.

Hackford, J. E., Lawson, S., and Spielmann, P. E., 1931. On an asphalt ring from Ur of the Chaldees. *Journal of the Institute Petroleum Technology*, **17**(98), 738.

Hansson, M. C., and Foley, B. P., 2008. Ancient DNA fragments inside classical Greek amphoras reveal cargo of 2400-year-old shipwreck. *Journal of Archaeological Science*, **35**(5), 1169–1176.

Hardy, K., Blakeney, T., Copeland, L., Kirkham, J., Wrangham, R., and Collins, M., 2009. Starch granules, dental calculus and new perspectives on ancient diet. *Journal of Archaeological Science*, **36**(2), 248–255.

Haslam, M., 2004. The decomposition of starch grains in soils: implications for archaeological residue analyses. *Journal of Archaeological Science*, **31**(12), 1715–1734.

Heaton, K., Solazzo, C., Collins, M. J., Thomas-Oates, J., and Bergström, E. T., 2009. Towards the application of desorption electrospray ionisation mass spectrometry (DESI-MS) to the analysis of ancient proteins from artefacts. *Journal of Archaeological Science*, **36**(10), 2145–2154.

Henderson, J. S., Joyce, R. A., Hall, G. R., Hurst, W. J., and McGovern, P. E., 2007. Chemical and archaeological evidence for the earliest cacao beverages. *Proceedings of the National Academy of Sciences*, **104**(48), 18937–18940.

Henry, A. G., and Piperno, D. R., 2008. Using plant fossils from dental calculus to recover human diet: a case study from Tell al-Raqā'i, Syria. *Journal of Archaeological Science*, **35**(7), 1943–1950.

Heron, C. P., and Evershed, R. P., 1995. The analysis of organic residues and the study of pottery use. In Schiffer, M. B. (ed.), *Archaeological Method and Theory*. Tucson: University of Arizona Press, Vol. 5, pp. 247–284.

Heron, C. P., Evershed, R. P., Goad, L. J., and Denham, V., 1991. New approaches to the analysis of organic residues from archaeological remains. In Budd, P., Chapman, B., Jackson, C., Janaway, R., and Ottaway, B. (eds.), *Archaeological Sciences 1989: Proceedings of a Conference on the Application of Scientific Techniques to Archaeology, Bradford, September 1989*. Oxford: Oxbow. Oxbow Monograph, Vol. 9, pp. 332–339.

Heron, C. P., Nemcek, N., Bonfield, K. M., Dixon, D., and Ottaway, B. S., 1994. The chemistry of Neolithic beeswax. *Naturwissenschaften*, **81**(6), 266–269.

Heron, C., Nilsen, G., Stern, B., Craig, O. E., and Nordby, C., 2009. Norway's first exploitation of oil? The processing of marine mammal blubber in slab-lined pits (Goldschmidt Conference Abstracts 2009 – I). *Geochimica et Cosmochimica Acta*, **73**(13), A525.

Hornsey, I. S., 2003. *History of Beermaking and Brewing*. Cambridge: Royal Society of Chemistry.

Jones, M., 2001. *The Molecule Hunt: Archaeology and the Hunt for Ancient DNA*. London: Penguin.

Lee-Thorp, J. A., 2008. On isotopes and old bones. *Archaeometry*, **50**(6), 925–950.

Loy, T. H., 1983. Prehistoric blood residues: detection on tool surfaces and identification of species of origin. *Science*, **220**(4603), 1269–1271.

Loy, T. H., and Hardy, B. L., 1992. Blood residue analysis of 90,000-year-old stone tools from Tabun Cave, Israel. *Antiquity*, **66**(250), 24–35.

Loy, T. H., and Wood, A. R., 1989. Blood residue analysis at Çayönü Tepesi, Turkey. *Journal Field Archaeology*, **16**(4), 451–460.

Manning, A. P., 1994. A cautionary note on the use of Hemastix and Dot-blot Assays for the detection and confirmation of archaeological blood residues. *Journal of Archaeological Science*, **21**(2), 159–162.

McGovern, P. E., Glusker, D. L., Exner, L. J., and Voigt, M. M., 1996. Neolithic resinated wine. *Nature*, **381**(6582), 480–481.

McGovern, P. E., Hartung, U., Badler, V. R., Glusker, D. L., and Exner, L. J., 1997. The beginnings of winemaking and viniculture in the ancient Near East and Egypt. *Expedition*, **39**(1), 3–21.

McGovern, P. E., Zhang, J., Tang, J., Zhang, Z., Hall, G. R., Moreau, R. A., Nuñez, A., Butrym, E. D., Richards, M. P., Wang, C.-S., Cheng, Z., Zhao, Z., and Wang, C., 2004. Fermented beverages of pre- and proto-historic China. *Proceedings of the National Academy of Sciences*, **101**(51), 17593–17598.

McMurry, J. E., 2004. *Organic Chemistry*, 6th edn. Belmont: Thomson Brooks/Cole.

Mercader, J., Bennett, T., and Raja, M., 2008. Middle Stone Age starch acquisition in the Niassa Rift, Mozambique. *Quaternary Research*, **70**(3), 283–300.

Michel, F. A., 1998. The relationship of massive ground ice and the late Pleistocene history of northwest Siberia. *Quaternary International*, **45–46**, 43–48.

Michel, R. H., McGovern, P. E., and Badler, V. R., 1992. Chemical evidence for ancient beer. *Nature*, **360**(6399), 24.

Michel, R. H., McGovern, P. E., and Badler, V. R., 1993. The first wine and beer. *Analytical Chemistry*, **65**(8), 408A–413A.

Mills, J. S., and White, R., 1977. Natural resins of art and archaeology their sources, chemistry, and identification. *Studies in Conservation*, **22**(1), 12–31.

Mirabaud, S., Rolando, C., and Regert, M., 2007. Molecular criteria for discriminating adipose fat and milk from different species by NanoESI MS and MS/MS of their triacylglycerols: application to archaeological remains. *Analytical Chemistry*, **79**(16), 6182–6192.

Newman, M. E., Yohe, R. M., II, Ceri, H., and Sutton, M. Q., 1993. Immunological protein residue analysis of non-lithic archaeological materials. *Journal of Archaeological Science*, **20**(1), 93–100.

O'Leary, M. H., 1981. Carbon isotope fractionation in plants. *Phytochemistry*, **20**(4), 553–567.

Outram, A. K., Stear, N. A., Bendrey, R., Olsen, S., Kasparov, A., Zaibert, V., Thorpe, N., and Evershed, R. P., 2009. The earliest horse harnessing and milking. *Science*, **323**(5919), 1332–1335.

Perry, L., 2001. *Prehispanic Subsistence in the Middle Orinoco Basin: Starch Analyses Yield New Evidence*. Unpublished Ph.-D. dissertation, Department of Anthropology, Southern Illinois University, Carbondale.

Piperno, D. R., and Holst, I., 1998. The presence of starch grains on prehistoric stone tools from the humid neotropics: indications of early tuber use and agriculture in Panama. *Journal of Archaeological Science*, **25**(8), 765–776.

Piperno, D. R., Ranere, A. J., Holst, I., and Hansell, P., 2000. Starch grains reveal early root crop horticulture in the Panamanian tropical forest. *Nature*, **407**(6806), 894–897.

Piperno, D. R., Weiss, E., Holst, I., and Nadel, D., 2004. Processing of wild cereal grains in the Upper Palaeolithic revealed by starch grain analysis. *Nature*, **430**(7000), 670–673.

Piperno, D. R., Ranere, A. J., Holst, I., Iriarte, J., and Dickau, R., 2009. Starch grain and phytolith evidence for early ninth millennium B.P. maize from the Central Balsas River Valley, Mexico. *Proceedings of the National Academy of Sciences*, **106**(13), 5019–5024.

Pollard, A. M., and Heron, C., 2008. *Archaeological Chemistry*, 2nd edn. Cambridge: Royal Society of Chemistry.

Pollard, A. M., Batt, C., Stern, B., and Young, S. M. M., 2007. *Analytical Chemistry in Archaeology*. Cambridge: Cambridge University Press.

Pramanik, B. N., Ganguly, A. K., and Gross, M. L., 2002. *Applied Electrospray Mass Spectrometry*. New York: Marcel Dekker.

Reber, E. A., and Evershed, R. P., 2004a. Identification of maize in absorbed organic residues: a cautionary tale. *Journal of Archaeological Science*, **31**(4), 399–410.

Reber, E. A., and Evershed, R. P., 2004b. How did Mississippians prepare maize? The application of compound-specific carbon isotope analysis to absorbed pottery residues from several Mississippi valley sites. *Archaeometry*, **46**(1), 19–33.

Reichert, E. T., 1913. *The Differentiation and Specificity of Starches in Relation to Genera, Species, etc*. Washington, DC: Carnegie Institution.

Rice, P. M., 1987. *Pottery Analysis: A Sourcebook*. Chicago: University of Chicago Press.

Richards, T. W., 1895. The composition of Athenian pottery. *American Chemical Journal*, **17**(3), 152–154.

Rottländer, R. C. A., and Hartke, I., 1982. New results of food identification by fat analysis. In Aspinall, A., and Warren, S. E. (eds.), *Proceedings of the 22nd Symposium on Archaeometry:*

Held at the University of Bradford, Bradford, U.K., 30th March–3rd April 1982. Bradford: Schools of Physics and Archaeological Sciences, University of Bradford, pp. 218–221.
Salque, M., Bogucki, P. I., Pyzel, J., Sobkowiak-Tabaka, I., Grygiel, R., Szmyt, M., and Evershed, R. P., 2013. Earliest evidence for cheese making in the sixth millennium BC in northern Europe. *Nature*, **493**(7433), 522–525.
Samuel, D., 1996. Investigation of ancient Egyptian baking and brewing methods by correlative microscopy. *Science*, **273**(5274), 488–490.
Schwarz, C., Debruyne, R., Kuch, M., McNally, E., Schwarcz, H., Aubrey, A. D., Bada, J., and Poinar, H., 2009. New insights from old bones: DNA preservation and degradation in permafrost preserved mammoth remains. *Nucleic Acids Research*, **37**(10), 3215–3229.
Smith, P. R., and Wilson, M. T., 1992. Blood residues on ancient tool surfaces: a cautionary note. *Journal of Archaeological Science*, **19**(3), 237–241.
Smith, P. R., and Wilson, M. T., 2001. Blood residues in archaeology. In Brothwell, D. R., and Pollard, A. M. (eds.), *Handbook of Archaeological Sciences*. Chichester: Wiley, pp. 313–332.
Solazzo, C., Fitzhugh, W. W., Rolando, C., and Tokarski, C., 2008. Identification of protein remains in archaeological potsherds by proteomics. *Analytical Chemistry*, **80**(12), 4590–4597.
Spangenberg, J. E., Jacomet, S., and Schibler, J., 2006. Chemical analyses of organic residues in archaeological pottery from Arbon Bleiche 3, Switzerland – evidence for dairying in the late Neolithic. *Journal of Archaeological Science*, **33**(1), 1–13.
Stankiewicz, B. A., Hutchins, J. C., Thomson, R., Briggs, D. E., and Evershed, R. P., 1997. Assessment of bog-body tissue preservation by pyrolysis-gas chromatography/mass spectrometry. *Rapid Communications in Mass Spectrometry*, **11**(17), 1884–1890.
Steele, V. J., Stern, B., and Stott, A. W., 2010. Olive oil or lard?: distinguishing plant oils from animal fats in the archeological record of the eastern Mediterranean using gas chromatography/combustion/isotope ratio mass spectrometry. *Rapid Communications in Mass Spectrometry*, **24**(23), 3478–3484.
Stern, B., Heron, C., Serpico, M., and Bourriau, J., 2000. A comparison of methods for establishing fatty acid concentration gradients across potsherds: a case study using Late Bronze Age Canaanite amphorae. *Archaeometry*, **42**(2), 399–414.
Stern, B., Heron, C., Tellefsen, T., and Serpico, M., 2008. New investigations into the Uluburun resin cargo. *Journal of Archaeological Science*, **35**(8), 2188–2203.
Stevens, S. M., Jr., Wolverton, S., Venables, B., Barker, A., Seeley, K. W., and Adhikari, P., 2010. Evaluation of microwave-assisted enzymatic digestion and tandem mass spectrometry for the identification of protein residues from an inorganic solid matrix: implications in archaeological research. *Analytical and Bioanalytical Chemistry*, **396**(4), 1491–1499.
White, R. E., 2006. *Principles and Practice of Soil Science: The Soil as a Natural Resource*, 4th edn. Malden: Blackwell.
Wilson, J., Hardy, K., Allen, R., Copeland, L., Wrangham, R., and Collins, M., 2010. Automated classification of starch granules using supervised pattern recognition of morphological properties. *Journal of Archaeological Science*, **37**(3), 594–604.

Cross-references

Fourier Transform Infrared Spectroscopy (FTIR)
Gas Chromatography
Ötzi, the Tyrolean Iceman

ÖTZI, THE TYROLEAN ICEMAN

James H. Dickson
Dickson Laboratory for Bioarchaeology,
York Archaeological Trust, Glasgow, UK

Sometimes called the Tyrolean Iceman and often given the humanizing nickname Ötzi, the body of this late Neolithic (Chalcolithic or Copper Age) male was found in September of 1991 and became famous instantly. Mummified by freezing, his body is very well preserved, though shriveled and damaged by the rough recovery. There were several items of clothing and varied personal equipment, some poorly preserved. The items of gear were found up to 5 m from the body, but all are usually assumed to have been his possessions.

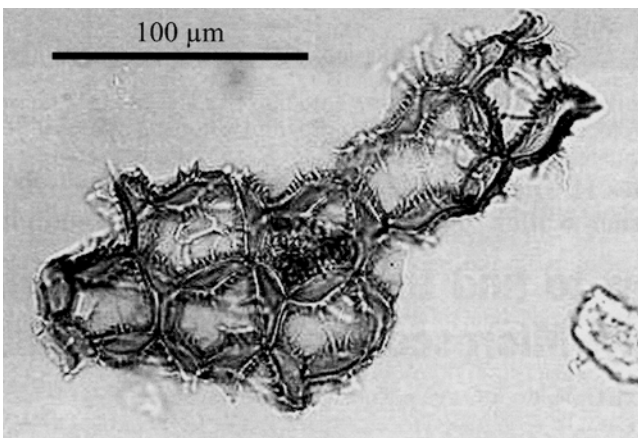
Especially important are a complete copper-headed ax, an unfinished longbow with a quiver containing 14 arrows, incomplete or broken, and a belted pouch containing a fire-making kit with true tinder fungus, flints and pyrites, and a retouching tool. The grass cape, fur cap, well-crafted shoes, and all other items of clothing are unparalleled finds from the European Neolithic. This mummy of a man some 46 years of age with many of his garments and objects is unique and totally unexpected. Its discovery is of great archaeological importance because it preserves body soft tissues and other organic materials that do not normally survive so long into the present.

On the basis of many radiocarbon dates, Ötzi lived 5,200–5,300 years ago. The numerous radiocarbon dates were obtained from body tissues, the equipment, leather, hair, charcoal, bast fibers of the tree *Tilia* (used for bindings), and low altitude grasses from the clothes; they all produce a perfectly homogeneous series. That his body was preserved by freezing so quickly is taken as evidence of increasing cold with advancing glaciers in the Alps around 5,000 years ago – the Neoglaciation. In the late twentieth century, the corpse finally melted out of ice at 3,210 m a.s.l. on the main divide of the Alps about 92 m inside Südtirol, Italy. Topographically, the site is at the very uppermost part of the Ötztal, within the drainage that flows through Austria to the Danube and the Black Sea.

Housed in the Iceman Museum in Bolzano, Südtirol, the corpse is not a typical glacier mummy. Bodies melted out from glaciers have usually been broken into pieces by the downhill movement of the ice. This mummy was trapped within a -boulder-strewn, rock-cut hollow, which was overridden crosswise by the ice (Figure 1). Any movement of the body was a matter of a few meters, and it was likely caused by melt water during some period or periods of milder climate.

Many interpretations of the Iceman, especially his lifestyle and death, are controversial. What we can know with some confidence is that Ötzi had died quickly by an arrow shot into his back under the left shoulder, probably in the immediate vicinity in which his body was found. The death occurred while food from his last meal remained in the stomach sensu stricto. The arrow had pierced the scapula, ruptured the subclavicular artery, and led to

Oxygen Isotopes, Figure 1 Ötzi was discovered within a protected, ice-covered hollow that lay directly beneath the standing men (Photograph looking southeast taken in late summer of 2000 by James H. Dickson).



Oxygen Isotopes, Figure 2 The tiny leaf fragment of the bog moss *Sphagnum imbricatum* sensu lato, a low altitude species, recovered from Ötzi's colon Botanical Institute, Innsbruck.

profuse blood loss. He had been very active during the last hours of his life, having descended from a high to a low elevation, then having ascended back to a higher location. This journey was deduced from the presence of pollen (crucially that of *Ostrya carpinifolia*) and submicroscopic plant remains, including mosses, extracted from the stomach, ileum, colon, and rectum. During his complex final travels, his right palm was badly and deeply cut down to the bone between the thumb and index finger. The wound may have been staunched by bog moss (*Sphagnum*), of which a tiny leaf fragment was found in the colon (Figure 2). The archaeobotanical evidence from the alimentary tract for spring/early summer as the season of death has not convinced everyone.

The location of the site in the towering mountainous topography is such that Ötzi's last journey was either southwards or northwards, not eastwards or westwards. That it was northwards is strongly indicated by the archaeology, and particularly the science, including notably the remains of plants such as the small tree *Ostrya carpinifolia* and the moss *Neckera complanata*. The likely route was from the Vinschgau (or Val Venosta) up the Schnalstal (or Val Senales), eventually to about 3 km northwest of the mountain Similaun where the body was later found.

Though the media promulgated the story that the Iceman died in "battle," such an interpretation is without any scientific justification, there being no peer-reviewed data ever having been published to sustain such an argument. What Ötzi's social role had been and the significance of his copper-bladed ax are especially controversial matters, difficult to resolve. The notion that Ötzi had been a herdsman, strongly espoused by Konrad Spindler, is very unlikely to be true. That he had apparently carried an unfinished bow and quiver with 14 useless arrows is enigmatic. A recent claim that the corpse had been buried on a "platform" at the very edge of the site has been rebutted by nine leading investigators.

The uniqueness of the discovery, the detailed nature of the diverse analyses, and the new and often dramatic findings over 20 years have led repeatedly to much untrammeled speculation in the media and on the web. There are numerous books, some of them trashy, that make scientifically unsupported claims, including one that labels the whole matter a hoax and another devoted to the "Curse of Ötzi."

Bibliography

Dickson, J. H., 2011. *Ancient Ice Mummies*. Stroud: The History Press.

Fleckinger, A. (ed.), 2011. *tzi 2.0: Eine Mumie zwischen Wissenschaft, Kult und Mythos von führenden Forschern aller beteiligten Fachgebiete*. Konrad Theiss, Stuttgart.

Kutschera, W., and Müller, W., 2003. "Isotope language" of the Alpine Iceman investigated with AMS and MS. *Nuclear Instruments and Methods in Physics Research B*, **204**, 705–719.

Spindler, K., 1993. *Der Mann im Eis: Die Ötztaler Mumie verrät die Geheimnisse der Steinzeit*. München: Bertelsmann Verlag.

Spindler, K., 1994. *The Man in the Ice: The Discovery of a 5,000-year-old Body Reveals the Secrets of the Stone Age*. New York: Harmony Books.

Zink, A., Graefen, A., Oeggl, K., Dickson, J., Leitner, W., Kaufmann, G., Fleckinger, A., Gostner, P., and Egarter-Vigl, E., 2011. The Iceman is not a burial: reply to Vanzetti et al. 2011. *Antiquity*, **85**(328): Project Gallery.

OXYGEN ISOTOPES

Lori E. Wright
Department of Anthropology, Texas A&M University, College Station, TX, USA

Definition

Stable oxygen isotope ratios are widely measured in archaeologically and paleontologically recovered bones and teeth as measures of climate change, geographic provenance, migration, and cultural behavior.

Oxygen isotope species

Stable isotopes are variants of atoms that differ in mass but do not decay over time, that is, they are not radioactive. The element oxygen (O) is found in three naturally occurring stable isotopes, ^{18}O, ^{17}O, and ^{16}O. The nucleus of each of these oxygen isotopes contains eight protons and either eight, nine, or ten neutrons, respectively. Of these stable isotopes, ^{16}O is the most abundant on earth, accounting for 99.757 % of atoms, while ^{17}O (0.038 %) and ^{18}O (0.205 %) occur in far smaller concentrations worldwide. Although some 17 unstable isotopes (which decay radioactively) are also known for oxygen, 14 of which are radiogenic (produced by the decay of other atoms), each of these isotopes has a half-life of 2 min or less, and therefore they do not factor appreciably into studies of oxygen isotope systematics in nature. The stable isotopes of oxygen behave equivalently in chemical reactions because they each have eight electrons in the reactive shell around the nucleus. Because they differ in mass, however, the rate at which these various isotopes of oxygen (or the isotopes of other elements for that matter) complete chemical reactions also differs, leading to uneven natural distributions of the isotopes. A difference in the isotopic ratio between the reactants and the product of a chemical reaction or physical state change is known as the *fractionation* of the isotopes (Fry, 2006).

Delta notation and standards

Stable isotope ratio mass spectrometers measure the content of various masses of a sample gas, such as carbon dioxide (CO_2), and compare those to a standard reference gas of known composition, alternating between the sample and standard gas to obtain a precise measurement. These ratios are then corrected to international standards to ensure interlaboratory comparability. $\delta^{18}O$ ratios can be calibrated either to the Vienna PeeDee Belemnite (vPDB) standard when measured on CO_2 or to the Vienna Standard Mean Ocean Water (vSMOW). Standards are defined by the International Atomic Energy Agency (IAEA). The ratio between the stable isotopes of oxygen is reported as a delta value, calculated as follows:

$$\delta^{18}O = [(R_{SAMPLE}/R_{STANDARD} - 1)] * 1000$$

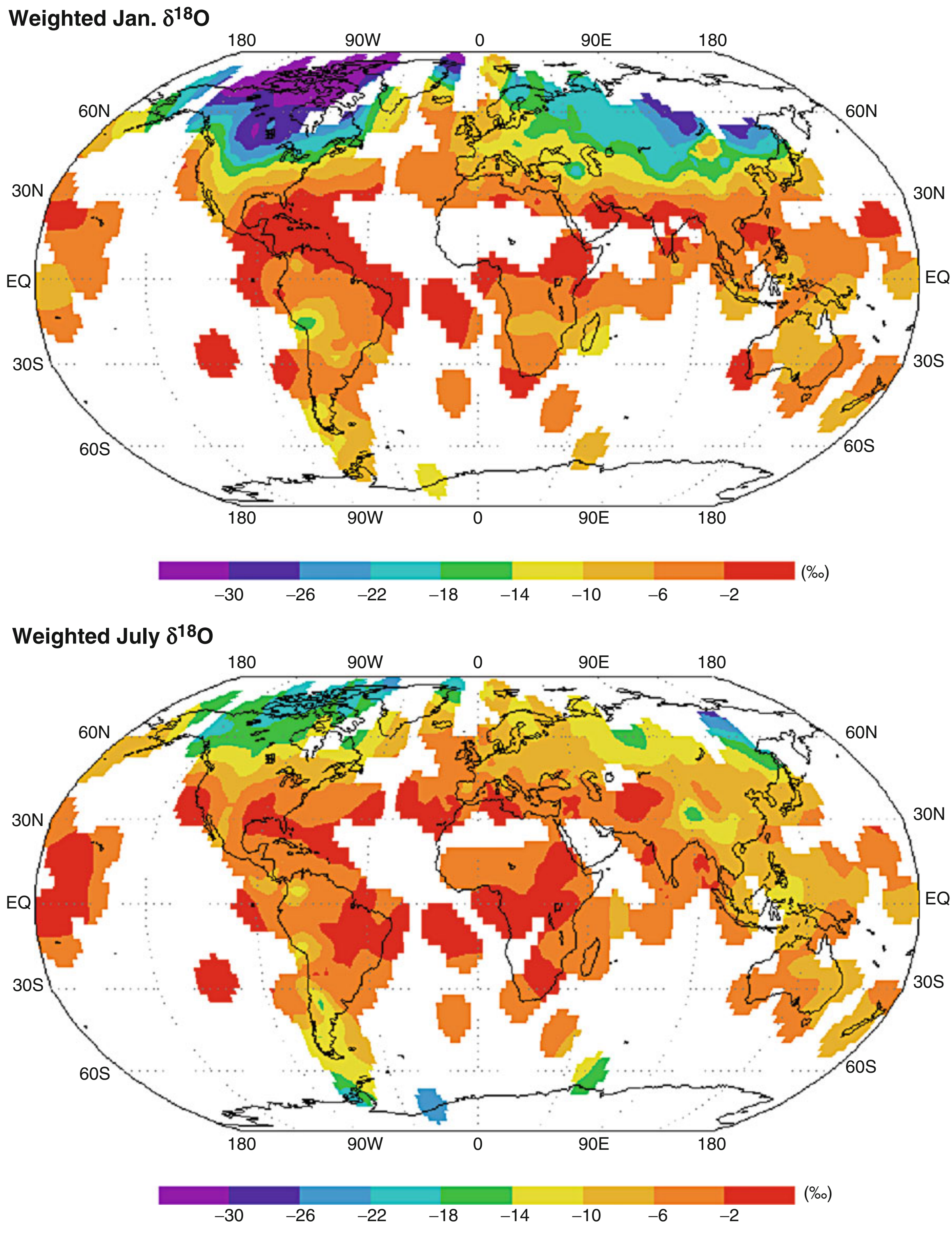
where $R = {}^{18}O/{}^{16}O$. This delta notation has the advantage of making small variations in the abundance of ^{18}O into larger, more manageable numbers. When measuring CO_2, which possesses one carbon and two oxygen atoms, a mass spectrometer has detectors set to measure the masses 44, 45, and 46, corresponding to the masses of $^{12}C^{16}O^{16}O$, $^{13}C^{16}O^{16}O$ or $^{12}C^{18}O^{16}O$, and $^{13}C^{18}O^{16}O$, which covers all the combinations of atomic weight in the stable CO_2 molecule. From these measurements, the abundances of the isotopes in the sample are calculated by comparison with their known abundance in a reference gas (Fry, 2006).

Oxygen isotopes in the global environment

Oxygen is found in most natural compounds, and it is ubiquitous in the tissues of living organisms as a result of its being the primary constituent of water, H_2O, though it is also found in most organic molecules. The isotopic ratios of natural systems are thus driven initially by global variation in the stable isotopic composition of water.

Global rainfall largely originates from oceanic water evaporated in the tropics. The "lighter" $H_2{}^{16}O$ (where the oxygen atom is ^{16}O) evaporates more quickly than the "heavier" $H_2{}^{18}O$, so the $\delta^{18}O$ of water in clouds and precipitation is low, i.e., negative on the vSMOW scale. As rain clouds travel over land, and as they move from warmer to cooler regions, the oxygen isotopic ratio of water held in the clouds declines further due to disproportionate condensation and precipitation of $H_2{}^{18}O$. As clouds move farther from their evaporative source, the remaining water is progressively depleted in ^{18}O. Subsequent evaporation of water from the earth's surface at higher latitudes also contributes to an increasingly "light" precipitation in temperate and polar regions, a process known as Rayleigh distillation. Thus, the isotopic ratio of rain that falls in latitudes far from the tropics contains proportionately less ^{18}O than rain in coastal tropical areas. Comparing the difference numerically, rain falling in coastal tropical regions has a $\delta^{18}O$ of approximately -5 ‰$_{SMOW}$, while this value declines with increasing latitude to as low as -30 ‰ in the Arctic. The $\delta^{18}O$ of rain also varies seasonally in accordance with changing temperature. Tropical air masses laden with ^{18}O condense when they encounter cooler air in temperate zones (Rozanski et al., 1993). Accordingly, the seasonal maps for global variation in the $\delta^{18}O$ of meteoric water differ considerably, as shown in Figure 1, which shows the global patterning in rainfall $\delta^{18}O$ (IAEA, 2006).

Terrestrial surface waters (rivers and lakes) derive from meteoric water; however, their isotopic composition is partly determined by mixing with other surface waters. For instance, lakes accumulate water over multiple seasons or years during which rainfall may differ in composition. Lakes and rivers also contribute water to the atmosphere through preferential evaporation of ^{16}O, which in turn leaves the remaining water in the reservoir further enriched in ^{18}O. When there is a pronounced dry season, such evaporative enrichment may lead to significantly higher $\delta^{18}O$ in lakes than in meteoric water. The effect of seasonal fluctuation in rain $\delta^{18}O$ on surface waters depends upon the proportional contribution of rain to the ground reservoirs throughout the year. In tropical areas, for example, most of the rain may fall during a short rainy season, while the limited dry season rainfall contributes little volume to surface reservoirs available to animals and plants (Lachniet and Patterson, 2009). In mountainous regions, $\delta^{18}O$ varies



Oxygen Isotopes, Figure 1 Amount-weighted monthly stable oxygen isotope ratio averages for global precipitation show a gradient from tropical to polar regions. The degree of this isotope change with latitude is seasonal: above = January, below = July (Data from the Global Network of Isotopes in Precipitation (IAEA, 2006)).

with elevation: higher altitudes receive rain of lower $\delta^{18}O$ than the adjacent lowlands, and the leeward side of mountain ranges may show isotopic rain shadows in accord with the path of prevailing climate systems. In piedmont areas, rivers may contain water that originated as rainfall at high elevation on nearby mountains, and thus they may contain lower $\delta^{18}O$ than local meteoric water. Such factors influence the $\delta^{18}O$ of water available to plants and animals in local habitats, contributing to considerable diversity in $\delta^{18}O$ ratios across a landscape.

Water in the body and skeleton

The $\delta^{18}O$ of body tissues in all living organisms roughly follows the same global patterning in isotope ratios that is fundamentally shaped by rainfall $\delta^{18}O$ patterns. In this way, $\delta^{18}O$ can serve as a natural tracer (Schwarcz and Schoeninger, 1991). Although food contributes a small amount of oxygen to body tissues, imbibed water is the largest contributor to the body water pool (Longinelli, 1984; Luz et al., 1990; Bryant and Froelich, 1995; Kohn, 1996). In humans, as in other mammals, body water is typically enriched in the ^{18}O isotope, relative to imbibed water (presumably derived from rainfall), due to the disproportionately greater loss of ^{16}O in CO_2 from respiration as well as urine and sweat.

Skeletal tissues, such as bones and teeth, contain oxygen as components of both collagen and bone mineral. Skeletal hard tissues are precipitated in equilibrium with bicarbonate ions in the body water pool. The $\delta^{18}O$ of apatite precipitated in skeletal mineral is typically enriched in ^{18}O relative to the body water $\delta^{18}O$. This offset is species specific, since the magnitude of the fractionation that occurs in mineral precipitation is dependent on body temperature (Urey, 1947; Lécuyer et al., 2010), which varies among animal species. Bone mineral is composed of a poorly crystalline carbonated hydroxyapatite, $Ca_5(PO_4)_3(OH)$. Oxygen can be readily acquired for analysis from carbonate (CO_3) groups that substitute for the hydroxyl or phosphate groups within the hydroxyapatite or are adsorbed onto crystal surfaces. Bone phosphate $\delta^{18}O$ values are typically positive on the vSMOW scale, although bone carbonate contains proportionately less ^{18}O than the vPDB standard and thus shows mostly negative values on that scale.

For carbonate samples, carbon dioxide gas is typically collected by reacting powdered bone mineral with 100 % orthophosphoric acid under vacuum in a sealed reaction system (an Isocarb or Kiel peripheral) attached to a mass spectrometer. Oxygen bound within phosphate (PO_4) groups of hydroxyapatite is more difficult to prepare, often by reaction with bromine to produce silver orthophosphate, which is needed to separate it from the carbonate ions in hydroxyapatite (Stuart-Williams and Schwarcz, 1995). Newer methods using a thermal conversion elemental analyzer (TCEA) with continuous flow mass spectrometry may soon facilitate greater accuracy with smaller phosphate samples (Wiedemann-Bidlack et al., 2008; LaPorte et al., 2009). $\delta^{18}O$ measurements may also be collected through laser ablation of tooth surfaces (Cerling and Sharp, 1996), although it is not clear whether these data are derived from oxygen in carbonate alone or also from phosphate oxygen. A new instrument, the sensitive high-resolution ion microprobe (SHRIMP), is a secondary ion mass spectrometer that probes tiny and invisible spots on the surface of samples such as teeth (Aubert et al., 2012). Presumably, carbonates are the primary source of these ions, as with laser ablation. Although carbonate and phosphate $\delta^{18}O$ are highly correlated in paired samples (Iacumin et al., 1996), it is possible that carbonate signals attenuate a longer period of enamel maturation, since they appear to show slightly less seasonal fluctuation in $\delta^{18}O$ than does phosphate (Pellegrini et al., 2011).

Bone is subject to considerable postdepositional chemical transformation, or diagenesis, because of its porosity and high collagen content. Thus, archaeological applications of $\delta^{18}O$ analyses need to consider the biological integrity of the isotope ratios measured. The addition of exogenous ions and recrystallization of original bone mineral (with fractionation) can be detected by a variety of methods, such as looking at the crystallinity of the sample using Fourier transform infrared spectroscopy (FTIR) (Wright and Schwarcz, 1996; Kohn et al., 1999; Sponheimer and Lee-Thorp, 1999a; Lee-Thorp and Sponheimer, 2003). More recent work has emphasized tooth enamel as a sample material because of its greater resistance to diagenetic exchange than bone (Sponheimer and Lee-Thorp, 1999b), with both carbonate and phosphate frequently studied.

Climate

Oxygen isotope measurements from ocean sediment cores provide a record of climate change in the past. Oceanic sediments contain the carbonate skeletons of Foraminifera that fall to the ocean floor after the death of the organism, as well as pollen and other organic particles. Because the fractionation of $\delta^{18}O$ is temperature dependent (Urey, 1947), the measured $\delta^{18}O$ serves as a proxy for ancient oceanic temperature. Data from such cores has been used to reconstruct climate change during the Quaternary period, and it shows oscillating periods of warmer and cooler seawater (Emiliani, 1957). These periods are known as oxygen, or marine, isotope stages (OIS or MIS). Sediments with higher $\delta^{18}O$ identify stages that correspond to glaciations, while sediments with lower $\delta^{18}O$ were deposited during warmer interglacial intervals. The fluctuating $\delta^{18}O$ values of seawater are not directly related to temperature. They are now understood to be the result of changes in volume of the glacial ice sheets, which preferentially removes ^{16}O from the ocean. The climate fluctuation documented in these sea cores, and confirmed in core data from glaciers, is understood to be a result of fluctuating warming by the sun caused by changes in the tilt of the earth's rotational axis, known as Milankovitch cycles (Imbrie et al., 1984).

In archaeology, climate change has also been explored through stable oxygen isotopic analysis of prehistoric fauna (Longinelli, 1984; Luz and Kolodny, 1989). This kind of paleontological analysis is a growing field, with research underway on local climate sequences around the world. Many studies explore ancient climate variability through the analysis of archaeologically dated mollusks (Kennett and Voorhies, 1995), herbivore teeth (Bryant et al., 1994; Fabre et al., 2011), and other archaeological materials.

Migration in human history

Soon after the first studies conducted on animals, research began using human bone as the sample material to distinguish the skeletons of immigrants who were buried far from their lands of origin (Schwarcz et al., 1991; Stuart-Williams et al., 1996; White et al., 1997). In this approach, stable oxygen isotopes are measured in a number of skeletons. Depending on the nature of the skeletal sample analyzed, a local skeletal δ^{18}O ratio is determined, either from the variability of the δ^{18}O data collected or by comparison with data from other nearby sites. If human samples are numerous enough, and if there is reason to believe that most of the skeletons were local residents (e.g., burials from a typical cemetery or settlement), a statistical approach to the identification of outliers may be practical (Wright, 2012). Skeletons with δ^{18}O ratios that differ from the local value can be interpreted as immigrants or foreigners. In contrast to strontium isotopes, which are also used for tracking migration in the ancient past, δ^{18}O ratios from animal remains do not provide a comparable local environmental proxy for humans living in the same area because animal body temperatures vary by species, and fractionation of δ^{18}O during bone formation is temperature dependent. Moreover, both wild and domestic fauna may not have access to water of the same isotopic ratio as the humans who consume them and leave their bones to be recovered within ancient sites. Estimating local bone δ^{18}O values from modern surface water data turns out to be surprisingly complicated (Bell et al., 2009, 2010; Millard and Schroeder, 2010), perhaps due in part to varied contributions to bone isotope ratios from food (Daux et al., 2008). Additionally, error in estimating the δ^{18}O of drinking water from human bone values is considerable, raising doubt about the specificity of this approach (Pollard et al., 2011). Many researchers wrestle with the difficulty of defining a local value for human δ^{18}O due to variability in the water sources potentially exploited by humans. In the Andes, for example, rivers bring highland water to the piedmont and coast (Knudson, 2009; Turner et al., 2009). Direct comparison to human skeletal data from potential homelands is perhaps the most reliable approach.

Stable oxygen isotopes have been used to document migration in varied parts of the world. In Mesoamerica, oxygen isotopes have revealed complex patterns of military recruitment and long distance warfare at the state of Teotihuacan (White et al., 1997, 2002; Spence et al., 2004). In highland Guatemala, most nonlocal skeletons in elite tombs appear to be from the lowland Maya area, rather than central Mexico (Wright et al., 2010), as was suggested by archaeologists. Studies of large urban communities such as Rome (Prowse et al., 2007), Roman Winchester (Eckardt et al., 2009), Tombos in Egypt (Buzon and Bowen, 2010), and Tikal (Wright, 2012) have identified a considerable proportion of migrants, suggesting that immigration contributed to population growth of these states.

Oxygen isotope values are not unique to individual sites, and numerous locales may share equivalent values. Therefore, stable oxygen isotope analysis is most useful in identifying migrants from very distant environmental contexts that differ substantially in climate. For instance, recent studies have sought to identify African slaves (migrants) in Mexico (Price et al., 2012), Vikings in Ireland (Knudson et al., 2012b), etc. The strength of these interpretations is greatly improved by combining several isotopic methods, including stable strontium, carbon, nitrogen, lead, and sulfur isotopes (see, e.g., Turner et al., 2009; Oelze et al., 2012; Laffoon et al., 2013).

Breastfeeding and cultural practices

Teeth also provide the advantage of registering body water isotopic composition for a limited span of development, unlike bone, which is continually reworked by remodeling systems with osteoclast cells that tunnel through bone and osteoblast cells that rebuild it. While bone isotopes are biased in reflecting the ages of late adolescence when the skeleton reaches its maximal size (Hedges et al., 2007), bones also incorporate food and water consumed throughout life. Tooth enamel is not remodeled after it is deposited, and it retains the isotopic composition of childhood water intake, when it mineralized. Body water is enriched in ^{18}O when compared to drinking water; thus nursing infants show higher body water δ^{18}O than their mothers (Roberts et al., 1988). This principle explains the higher δ^{18}O signature of teeth that form early in postnatal life when infants are nursing, such as permanent first molars, as compared to teeth that form during older childhood (Wright and Schwarcz, 1998).

Because the duration of nursing is highly variable, both within and among cultures, as are the complementary feeding practices for older infants (Dettwyler and Fishman, 1992), δ^{18}O analyses of teeth provide a means to explore nursing duration in the past. Among the Maya, $\delta^{18}O$ differences among teeth suggest that children may have nursed to more than 5 years of age (Wright and Schwarcz, 1998). Oxygen isotopes have also been used to study nursing in Roman skeletons (Dupras and Tocheri, 2007). This nursing effect should also be kept in mind when selecting teeth as samples for migration studies, since $\delta^{18}O$ may even vary within a single tooth crown due to a change in nursing behavior (Wright, 2013).

Beyond breastfeeding, little research has yet been done on the effect of other cultural practices on $\delta^{18}O$ in humans. Daux et al. (2008) have shown that $\delta^{18}O$ of cooked food is higher than that of local drinking water due to evaporative enrichment. Social variability in access to water sources and water storage methods might introduce some variability in $\delta^{18}O$, especially in complex societies, where restricted access to certain water reservoirs or socially distinct culinary practices might distinguish status groups.

Because the teeth of many mammals grow for extended periods of time, they contain a record of seasonal changes in animal body water $\delta^{18}O$. This has been exploited to investigate seasonal hunting and fishing practices (Hufthammer et al., 2010), as well as the management of domestic sheep herds (Henton et al., 2010; Blaise and Balasse, 2011). Where pastoralists were involved in long distance trade, $\delta^{18}O$ may shed light on the geographic origin of mobile animals, as in the case of Andean camelids (Knudson et al., 2012a).

The rate of research on $\delta^{18}O$ in both human and faunal samples from archaeological sites has increased exponentially over the last decade. New analytic methods and applications make this an exciting and very promising field of study.

Bibliography

Aubert, M., Williams, I. S., Boljkovac, K., Moffat, I., Moncel, M.-H., Dufour, E., and Grün, R., 2012. In situ oxygen isotope micro-analysis of faunal material and human teeth using a SHRIMP II: a new tool for palaeo-ecology and archaeology. *Journal of Archaeological Science*, **39**(10), 3184–3194.

Bell, L. S., Lee Thorp, J. A., and Elkerton, A., 2009. The sinking of the Mary Rose warship: a medieval mystery solved? *Journal of Archaeological Science*, **36**(1), 166–173.

Bell, L. S., Lee-Thorp, J. A., and Elkerton, A., 2010. Sailing against the wind: reply to Millard and Schroeder: 'True British sailors': a comment on the origin of the men of the Mary Rose. *Journal of Archaeological Science*, **37**(4), 683–686.

Blaise, E., and Balasse, M., 2011. Seasonality and season of birth of modern and late Neolithic sheep from south-eastern France using tooth enamel $\delta^{18}O$ analysis. *Journal of Archaeological Science*, **38**(11), 3085–3093.

Bryant, J. D., and Froelich, P. N., 1995. A model of oxygen isotope fractionation in body water of large mammals. *Geochimica et Cosmochimica Acta*, **59**(21), 4523–4537.

Bryant, J. D., Luz, B., and Froelich, P. N., 1994. Oxygen isotopic composition of fossil horse tooth phosphate as a record of continental paleoclimate. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **107**(3–4), 303–316.

Buzon, M. R., and Bowen, G. J., 2010. Oxygen and carbon isotope analysis of human tooth enamel from the New Kingdom site of Tombos in Nubia. *Archaeometry*, **52**(5), 855–868.

Cerling, T. E., and Sharp, Z. D., 1996. Stable carbon and oxygen isotope analysis of fossil tooth enamel using laser ablation. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **126** (1–2), 173–186.

Daux, V., Lécuyer, C., Héran, M.-A., Amiot, R., Simon, L., Fourel, F., Martineau, F., Lynnerup, N., Reychler, H., and Escarguel, G., 2008. Oxygen isotope fractionation between human phosphate and water revisited. *Journal of Human Evolution*, **55**(6), 1138–1147.

Dettwyler, K. A., and Fishman, C., 1992. Infant feeding practices and growth. *Annual Review of Anthropology*, **21**, 171–204.

Dupras, T. L., and Tocheri, M. W., 2007. Reconstructing infant weaning histories at Roman Period Kellis, Egypt using stable isotope analysis of dentition. *American Journal of Physical Anthropology*, **134**(1), 63–74.

Eckardt, H., Chenery, C., Booth, P., Evans, J. A., Lamb, A., and Müldner, G., 2009. Oxygen and strontium isotope evidence for mobility in Roman Winchester. *Journal of Archaeological Science*, **36**(12), 2816–2825.

Emiliani, C., 1957. Temperature and age analysis of deep-sea cores. *Science*, **125**(3244), 383–387.

Fabre, M., Lécuyer, C., Brugal, J.-P., Amiot, R., Fourel, F., and Martineau, F., 2011. Late Pleistocene climatic change in the French Jura (Gigny) recorded in the $\delta^{18}O$ of phosphate from ungulate tooth enamel. *Quaternary Research*, **75**(3), 605–613.

Fry, B., 2006. *Stable Isotope Ecology*. New York: Springer.

Hedges, R. E. M., Clement, J. G., Thomas, C. D. L., and O'Connell, T. C., 2007. Collagen turnover in the adult femoral mid-shaft: modeled from anthropogenic radiocarbon tracer measurements. *American Journal of Physical Anthropology*, **133**(2), 808–816.

Henton, E., Meier-Augenstein, W., and Kemp, H. F., 2010. The use of oxygen isotopes in sheep molars to investigate past herding practices at the Neolithic settlement of Çatalhöyük, Central Anatolia. *Archaeometry*, **52**(3), 429–449.

Hufthammer, A. K., Høie, H., Folkvord, A., Geffen, A. J., Andersson, C., and Ninnemann, U. S., 2010. Seasonality of human site occupation based on stable oxygen isotope ratios of cod otoliths. *Journal of Archaeological Science*, **37**(1), 78–83.

Iacumin, P., Bocherens, H., Mariotti, A., and Longinelli, A., 1996. Oxygen isotope analyses of co-existing carbonate and phosphate in biogenic apatite: a way to monitor diagenetic alteration of bone phosphate? *Earth and Planetary Science Letters*, **142** (1–2), 1–6.

IAEA, 2006. Isotope Hydrology Information System. The ISOHIS Database. Accessible at: http://www.iaea.org/water.

Imbrie, J., Hays, J. D., Martinson, D. G., McIntyre, A. C., Mix, A. C., Morley, J. J., Pisias, N. G., Prell, W. L., and Shackleton, N. J., 1984. The orbital theory of Pleistocene climate: support from a revised chronology of the marine del-18O record. In Berger, A., Imbrie, J., Hays, J., Kukla, G., and Saltzman, B. (eds.), *Milankovitch and Climate, Part 1*. Dordrecht: Reidel Publishing, pp. 269–305.

Kennett, D., and Voorhies, B., 1995. Middle Holocene periodicities in rainfall inferred from oxygen and carbon isotopic fluctuations in prehistoric tropical estuarine mollusc shells. *Archaeometry*, **37**(1), 157–170.

Knudson, K. J., 2009. Oxygen isotope analysis in a land of environmental extremes: the complexities of isotopic work in the Andes. *International Journal of Osteoarchaeology*, **19**(2), 171–191.

Knudson, K. J., Gardella, K. R., and Yaeger, J., 2012a. Provisioning Inka feasts at Tiwanaku, Bolivia: the geographic origins of camelids in the Pumapunku complex. *Journal of Archaeological Science*, **39**(2), 479–491.

Knudson, K. J., O'Donnabhain, B., Carver, C., Cleland, R., and Price, T. D., 2012b. Migration and Viking Dublin: paleomobility and paleodiet through isotopic analyses. *Journal of Archaeological Science*, **39**(2), 308–320.

Kohn, M. J., 1996. Predicting animal δ18O: accounting for diet and physiological adaptation. *Geochimica et Cosmochimica Acta*, **60**(23), 4811–4829.

Kohn, M. J., Schoeninger, M. J., and Barker, W. W., 1999. Altered states: effects of diagenesis on fossil tooth chemistry. *Geochimica et Cosmochimica Acta*, **63**(18), 2737–2747.

Lachniet, M. S., and Patterson, W. P., 2009. Oxygen isotope values of precipitation and surface waters in northern Central America (Belize and Guatemala) are dominated by temperature and amount effects. *Earth and Planetary Science Letters*, **284**(3), 435–446.

Laffoon, J. E., Valcárcel Rojas, R., and Hofman, C. L., 2013. Oxygen and carbon isotope analysis of human dental enamel from the Caribbean: implications for investigating individual origins. *Archaeometry*, **55**(4), 742–755.

LaPorte, D. F., Holmden, C., Patterson, W. P., Prokopiuk, T., and Eglington, B. M., 2009. Oxygen isotope analysis of phosphate: improved precision using TC/EA CF-IRMS. *Journal of Mass Spectrometry*, **44**(6), 879–890.

Lécuyer, C., Balter, V., Martineau, F., Fourel, F., Bernard, A., Amiot, R., Gardien, V., Otero, O., Legendre, S., Panczer, G., Simon, L., and Martini, R., 2010. Oxygen isotope fractionation between apatite-bound carbonate and water determined from controlled experiments with synthetic apatites precipitated at 10–37 degrees C. *Geochimica et Cosmochimica Acta*, **74**(7), 2072–2081.

Lee-Thorp, J., and Sponheimer, M., 2003. Three case studies used to reassess the reliability of fossil bone and enamel isotope signals for paleodietary studies. *Journal of Anthropological Archaeology*, **22**(3), 208–216.

Longinelli, A., 1984. Oxygen isotopes in mammal bone phosphate: a new tool for paleohydrological and paleoclimatological research? *Geochimica et Cosmochimica Acta*, **48**(2), 385–390.

Luz, B., and Kolodny, Y., 1989. Oxygen isotope variation in bone phosphate. *Applied Geochemistry*, **4**(3), 317–323.

Luz, B., Cormie, A. B., and Schwarcz, H. P., 1990. Oxygen isotope variations in phosphate of deer bones. *Geochimica et Cosmochimica Acta*, **54**(6), 1723–1728.

Millard, A. R., and Schroeder, H., 2010. 'True British sailors': a comment on the origin of the men of the *Mary Rose. Journal of Archaeological Science*, **37**(4), 680–682.

Oelze, V. M., Nehlich, O., and Richards, M. P., 2012. 'There's no place like home' – no isotopic evidence for mobility at the Early Bronze Age cemetery of Singen, Germany. *Archaeometry*, **54**(4), 752–778.

Pellegrini, M., Lee-Thorp, J. A., and Donahue, R. E., 2011. Exploring the variation of the $\delta^{18}O_p$ and $\delta^{18}O_c$ relationship in enamel increments. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **310**(1–2), 71–83.

Pollard, A. M., Pellegrini, M., and Lee-Thorp, J. A., 2011. Technical note: some observation on the conversion of dental enamel $\delta^{18}O_p$ values to $\delta^{18}O_w$ to determine human mobility. *American Journal of Physical Anthropology*, **145**(3), 499–504.

Price, D. T., Burton, J. H., Cucina, A., Zabala, P., Frei, R., Tykot, R. H., and Tiesle, V., 2012. Isotopic studies of human skeletal remains from a sixteenth to seventeenth century AD churchyard in Campeche, Mexico: diet, place of origin, and age. *Current Anthropology*, **53**(4), 396–433.

Prowse, T. L., Schwarcz, H. P., Garnsey, P., Knyf, M., Macchiarelli, R., and Bondioli, L., 2007. Isotopic evidence for age-related immigration to Imperial Rome. *American Journal of Physical Anthropology*, **132**(4), 510–519.

Roberts, S. B., Coward, W. A., Ewing, G., Savage, J., Cole, T. J., and Lucas, A., 1988. Effect of weaning on accuracy of doubly labeled water method in infants. *American Journal of Physiology – Regulatory, Integrative and Comparative Physiology*, **254**(4, Pt 2), R622–R627.

Rozanski, K., Araguás-Araguás, L., and Gonfiantini, R., 1993. Isotopic patterns in modern global precipitation. In Swart, P. K., Lohmann, K. C., McKenzie, J. A., and Savin, S. (eds.), *Climate Change in Continental Isotopic Records*. Washington, DC: American Geophysical Union. Geophysical Monograph, Vol. 78, pp. 1–36.

Schwarcz, H. P., and Schoeninger, M. J., 1991. Stable isotope analyses in human nutritional ecology. Yearbook of Physical Anthropology. *American Journal of Physical Anthropology*, **34** (S13), 283–321.

Schwarcz, H. P., Gibbs, L., and Knyf, M., 1991. Oxygen isotope analysis as an indicator of place of origin. In Pfeiffer, S., and Williamson, R. F. (eds.), *Snake Hill: An Investigation of a Military Cemetery from the War of 1812*. Toronto: Dundurn Press, pp. 263–268.

Spence, M. W., White, C. D., Longstaffe, F. J., and Law, K. R., 2004. Victims of the victims: human trophies worn by sacrificed soldiers from the Feathered Serpent Pyramid, Teotihuacan. *Ancient Mesoamerica*, **15**(1), 1–15.

Sponheimer, M., and Lee-Thorp, J. A., 1999a. Alteration of enamel carbonate environments during fossilization. *Journal of Archaeological Science*, **26**(2), 143–150.

Sponheimer, M., and Lee-Thorp, J. A., 1999b. Oxygen isotopes in enamel carbonate and their ecological significance. *Journal of Archaeological Science*, **26**(6), 723–728.

Stuart-Williams, H. L. Q., and Schwarcz, H. P., 1995. Oxygen isotopic analysis of silver orthophosphate using a reaction with bromine. *Geochimica et Cosmochimica Acta*, **59**(18), 3837–3841.

Stuart-Williams, H. L. Q., Schwarcz, H. P., White, C. D., and Spence, M. W., 1996. The isotopic composition and diagenesis of human bone from Teotihuacan and Oaxaca, Mexico. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **126** (1–2), 1–14.

Turner, B. L., Kamenov, G. D., Kingston, J. D., and Armelagos, G. J., 2009. Insights into immigration and social class at Machu Picchu, Peru based on oxygen, strontium, and lead isotopic analysis. *Journal of Archaeological Science*, **36**(2), 317–332.

Urey, H. C., 1947. The thermodynamic properties of isotopic substances. *Journal of the Chemical Society (London)*, **1947**, 562–581.

White, C. D., Spence, M. W., and Stuart-Williams, H. L. Q., 1997. The use of oxygen isotopes as environmental markers in ancient Mexico. *American Journal of Physical Anthropology*, **104**(Supplement 24), 238–239.

White, C. D., Spence, M. W., Longstaffe, F. J., Stuart-Williams, H., and Law, K. R., 2002. Geographic identities of the sacrificial victims from the Feathered Serpent pyramid, Teotihuacan: implications for the nature of state power. *Latin American Antiquity*, **13**(2), 217–236.

Wiedemann-Bidlack, F. B., Colman, A. S., and Fogel, M. L., 2008. Phosphate oxygen isotope analysis on microsamples of bioapatite: removal of organic contamination and minimization of sample size. *Rapid Communications in Mass Spectrometry*, **22**(12), 1807–1816.

Wright, L. E., 2012. Immigration to Tikal, Guatemala: evidence from stable strontium and oxygen isotopes. *Journal of Anthropological Archaeology*, **31**(3), 334–352.

Wright, L. E., 2013. Examining childhood diets at Kaminaljuyu, Guatemala, through stable isotopic analysis of sequential enamel microsamples. *Archaeometry*, **55**(1), 113–133.

Wright, L. E., and Schwarcz, H. P., 1996. Infrared and isotopic evidence for diagenesis of bone apatite at Dos Pilas, Guatemala: paleodietary implications. *Journal of Archaeological Science*, **23**(6), 933–944.

Wright, L. E., and Schwarcz, H. P., 1998. Stable carbon and oxygen isotopes in human tooth enamel: identifying breastfeeding and weaning in prehistory. *American Journal of Physical Anthropology*, **106**(1), 1–18. 106(3): 411.

Wright, L. E., Valdés, J. A., Burton, J. H., Price, T. D., and Schwarcz, H. P., 2010. The children of Kaminaljuyu: isotopic insight into diet and long distance interaction in Mesoamerica. *Journal of Anthropological Archaeology*, **29**(2), 155–178.

Cross-references

Field Geochemistry
Forensic Geoarchaeology
Fourier Transform Infrared Spectroscopy (FTIR)
Geochemical Sourcing
Lead Isotopes
Paleodiet
Paleoenvironmental Reconstruction
Stable Carbon Isotopes in Soils
Strontium Isotopes

P

PALEODEMOGRAPHY: METHODS AND RECENT ADVANCES

Maru Mormina
Department of Applied Social Studies, University of Winchester, Winchester, UK

Synonyms

Bioarchaeology; Evolutionary history; Human population history

Definition

Paleodemography refers to the description and explanation of biological adaptations, mortality, fertility, and migratory patterns of prehistoric populations, within the explanatory framework of evolutionary theory. Traditionally, paleodemography relied on morphological studies of bioarchaeological (bone material) evidence, although in recent years it has also been based on DNA and stable isotope evidence as well.

Introduction

Paleodemography is concerned with the impact of cultural and environmental change on the lives of past peoples. Once the preserve of paleontologists, anthropologists, and archaeologists, it now attracts biologists, geneticists, bioinformaticians, and chemists with fresh methods and perspectives that have made this field an exciting multidisciplinary endeavor. Knowledge of past human populations traditionally came from studying human osteological remains from archaeological contexts. The primary concern was the description and characterization of biological differences, and where temporal differences in skeletal morphology were found, these were interpreted in terms of migration and replacement. For example, the indigenous people of Tierra del Fuego (at the southern tip of South America) show a robust morphology, substantially different from the gracile morphology of other Amerindians. While this was initially interpreted as the result of the Fuegians belonging to an earlier migration into the continent (Lahr, 1995), other studies suggested that their morphology may reflect local adaptation to hard diets and extreme climate or long-term population isolation (Bernal et al., 2006). Further studies involving genetic analyses have now concluded that Fuegians and Amerindians share a common ancestry and come from the same migration that populated the rest of the Southern Cone (Perez et al., 2007, Perez et al., 2009). This example highlights how modern disciplines and new methodologies, such as genetics, can inform and change traditional paradigms in paleodemographic studies.

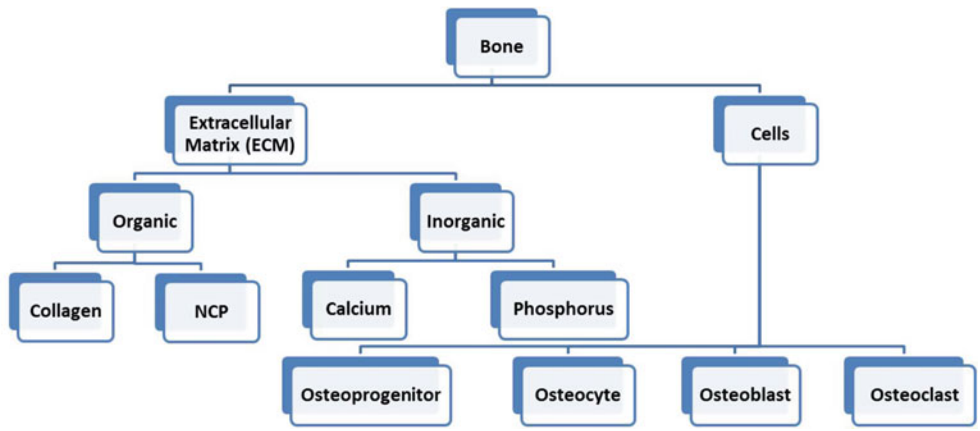
The first part of this review highlights the general methodological issues linked to paleodemographic studies (including the contribution of modern approaches such as genetics and isotope analyses); the second part discusses some of paleodemography's current topics.

Methods in paleodemography: issues and current advances

Sources of paleodemographic data: bioarchaeological material and preservation issues.

Our ability to reconstruct the life and lifestyle of past populations depends largely on the quantity and quality of the recovered archaeological finds. Biological material of paleodemographic interest is often not well preserved in archaeological sites. Hard tissue (primarily bone) is most commonly recovered, but, occasionally, soft (mummified) tissue can also be preserved, providing further opportunities for analysis. Other valuable sources in paleodemographic studies include hair and coprolites (fossilized feces). The information obtained from these different sources at the macroscopic, microscopic, and molecular levels provides alternative, and often

A.S. Gilbert (ed.), *Encyclopedia of Geoarchaeology*, DOI 10.1007/978-1-4020-4409-0,



Paleodemography: Methods and Recent Advances, Figure 1 Schematic representation of bone structure showing the varied components.

complementary, insights into the mobility, diet, social organization, environmental interactions, and biological adaptations of past people.

Skeletal material

Bone is the main source of biological material that is found within archaeological sites, as it has better chances of preservation than soft tissue. The amount and type of information that can be retrieved from the skeleton directly correlates with the sample's state of preservation. It is essential, therefore, to understand the chemical, physical, or biological changes that affect skeletal material in a burial context because they can introduce biases into the archaeological record that impact upon the analysis and interpretation of the data.

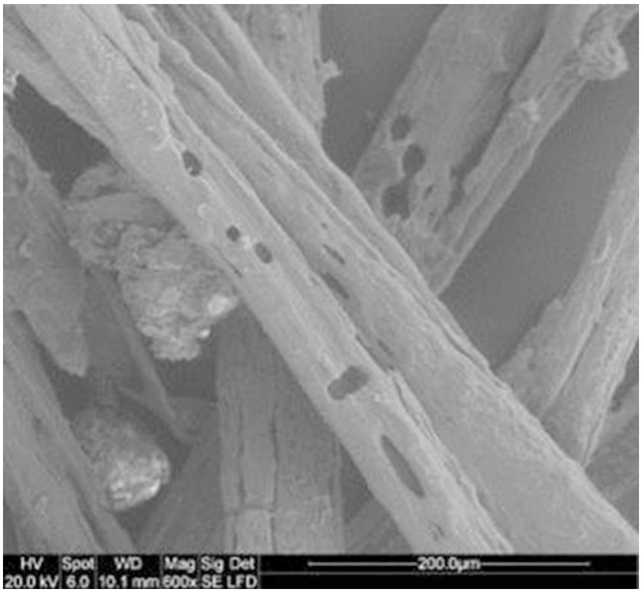
Bone (Figure 1) is a composite of mineral (mostly hydroxyapatite, a calcium phosphate complex) and protein (mostly collagen). Bone deteriorates through one or more of the following processes: (1) bacterial and fungal decay, (2) chemical loss of collagen, and (3) dissolution of the mineral phase. Bacterial decay is the most common and probably occurs early, when initial bone demineralization (due to soil pH, temperature, exposure to water, etc.) allows bacteria to access the collagen and initiate focal destruction (Collins et al., 2002). Bacterial degradation significantly affects bone preservation, increasing bone porosity and accelerating the demineralization process, thereby reducing the chances of collagen preservation and increasing the risk of contamination with exogenous biomolecules (Jans et al., 2004). Collagen loss occurs by hydrolysis or microbial attack (Hedges, 2002); the rate of degradation is time, pH, and temperature dependent (Collins et al., 2002). Broadly speaking, high temperatures and extreme pH accelerate collagen loss, and this alone can explain preservation differences among different archaeological sites (Hedges, 2002). Exposure to water plays an important role in the dissolution of the hydroxyapatite, which then exposes the collagen to bacterial degradation and hydrolysis, thus increasing crystallization and accelerating the fossilization process (Collins et al., 2002). Bones lying near water will also be more susceptible to solute uptake from the soil (e.g., uranium, carbon, and strontium), which greatly affects radiocarbon and isotopic analyses.

Hair

Hair is the most robust nonskeletal material of archaeological interest. Its strong molecular structure comes from high levels of keratin, a protein that constitutes the bulk of the fiber and is highly resistant to enzymatic attack, except by some specialized microorganisms (Kunert, 1989). The keratin coating also renders the hair insoluble in water and resistant to acids and alkali (Taylor et al., 1995). However, despite its relative robustness, hair can deteriorate rapidly. Although the process by which deterioration takes place is poorly understood, the main factor appears to be bacterial attack (Wilson et al., 2007, Wilson et al., 2010), though certain fungi can also degrade keratin, leaving characteristic tunnel-shaped lesions (DeGaetano et al., 1992) (Figure 2).

Coprolites

Coprolites are desiccated or mineralized feces, usually preserved in arid and temperate regions, which contain a variety of macroscopic and microscopic remains such as fibers, plant and animal residues, phytoliths, intestinal parasites, and pathogens, thereby providing information about health and lifestyle. Coprolites have not been extensively used in archaeological research, mainly due to the apparent lack of consensus in the way data are reported, making comparative analyses difficult (Bryant and Dean, 2006). Other limitations with its use are the usually small sample size, dependency on context, difficulties in associating particular coprolites with a species, and the risk of contamination through leaching. Moreover, coprolites are easily repositioned, making their stratigraphic context



Paleodemography: Methods and Recent Advances, Figure 2 Electron microscopy image (600× magnification) of hair shaft showing damage by fungal tunneling (Reproduced from (Bengtsson et al., 2011)).

less reliable. Even when animal or plant residues are detected, dietary extrapolations are complicated by issues of seasonality, quantity of food consumed, or eating patterns (Bryant and Dean, 2006). Macroscopic or microscopic inspection is often insufficient to distinguish human from nonhuman coprolites, but DNA recovered from coprolites can help with species identification (Reinhard and Bryant, 1992; Goldberg et al., 2009). However, leaching and contamination with DNA from other sources remains a major consideration; a recent study claiming to have recovered DNA from a human coprolite predating the Clovis occupation of the Americas acknowledged the possibility that the DNA could have come from later human populations and leached into a nonhuman coprolite (Gilbert et al., 2008).

Paleodemographic information at three levels of analysis: morphological, microscopic, and molecular.

Bioarchaeological material can provide invaluable information about past human populations, but issues of preservation and contamination must be considered carefully. Analyzing the samples at three levels reduces risk and provides complementary data.

Morphological analysis

Quantitative morphometric analyses have been the conventional approach to the study of bioarchaeological samples, providing information about sex, ancestry, health, diet, and adaptations. Traditional morphometry consists in applying multivariate statistical procedures to datasets of two-dimensional distances, angles, or distance ratios of anatomical structures. More recently, three-dimensional geometric morphometric methods using Cartesian coordinates have provided more robust results, as they preserve spatial information (Slice, 2007). Sometimes, morphometrics is the only way to analyze skeletal material – particularly when the sample's age or preservation precludes molecular studies – and it is used in determining paleodemographic parameters such as sex and age. Sexing relies on measurements of sexually dimorphic skeletal elements, typically the pelvis and skull (Scheuer, 2002), although long bones can also be highly informative (Özer and Katayama, 2008). Sexual dimorphism results from differential growth rates during adolescence and is largely genetic, though the effect of the environment (e.g., malnutrition and illness) is also considerable. Consequently, sexing a skeleton solely on size measures is often problematic (Meindl and Russell, 1998). Determining age at death relies on the skeleton's developmental characteristics (dentition patterns, bone size, shape, and degree of ossification), which are more accurately determined in the still-growing juvenile skeleton, while in the adult skeleton, age determination relies on measures of bone degeneration, though these can be affected by health and lifestyle factors (Franklin, 2010).

Morphological traits display a high degree of population variation, which represents a significant confounding factor when determining the age and sex of a skeleton. However, this variation has traditionally been used to determine ancestry, prehistoric migrations, and population continuity, particularly of extinct populations where DNA analysis is not possible. Regional differences of cranial and dental morphology have been used to understand the relationship between the Paleolithic inhabitants of Japan (the Jomon), the Neolithic farmers (the Yayoi), and the present-day Japanese (Ishida et al., 2009), whereas limb proportions have been used to understand the extent of climatic adaptations in the same populations (Temple et al., 2008), as interpopulation variation in the skeleton is also heavily influenced by the environment (Katzmarzyk and Leonard, 1998). Tooth morphology is closely linked to genetic background and geographical origins, and population affinities can therefore be tracked using dental anthropology. For example, differences of incidence of root and canal number in human populations have been suggested, with higher incidences of teeth with additional canals and roots occurring in Chinese, Australian, and sub-Saharan African populations and the lowest incidence in Western Eurasian, Japanese, and American Arctic populations (Cleghorn et al., 2007). Moreover, a recent study analyzing nine crown morphology traits in four contemporary Kenyan populations has suggested a strong correlation between dental morphology and genetic structure (Hubbard et al., 2015). In this study, the closest genetic and dental affinities were observed between population samples within each ethnic group and the greater divergence among samples from the different ethnic groups.

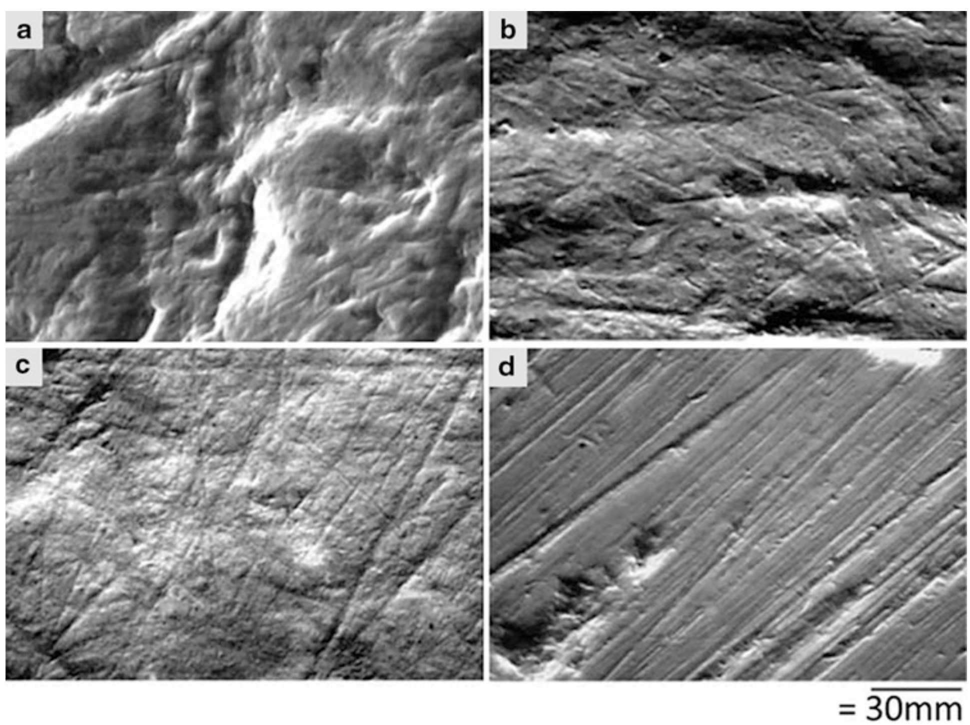
Microscopic analysis

Microscopic analysis of bone and dental structures, coprolites, and hair is routinely used alongside morphometric and other techniques to provide complementary information about diet, age, paleopathology, etc. For example, while macroscopic inspection of tooth size, allometry, and enamel thickness can indicate the mechanical properties and kind of foods a species is capable of eating, microwear patterns can reveal actual food preferences and/or consumption. Species that consume hard, brittle foods tend to show more pitting in their teeth, while those whose diet comprises hard leaves tend to present more striations (Figure 3). In fact, dental microwear in early *Homo* suggests that *H. erectus* may have consumed more hard and brittle foods than *H. habilis* (Ungar et al., 2006). An understanding of food preference in these early species has obvious implications for understanding the evolution of the genus *Homo*, including *H. sapiens*, which traditionally has been tied to changes in diet and environment.

Pathological conditions from archaeological bones are usually determined microscopically, though this is far from straightforward. In the case of tuberculosis (TB), a major infectious disease, determination relies on the presence of characteristic microscopic bone lesions, particularly in the vertebrae. However, only 5 % of TB sufferers develop bone tissue destruction, making this diagnostic marker unreliable, particularly given that in the pre-antibiotic era, infectious diseases such as TB were probably endemic (Donoghue et al., 2009). Parasitic remains provide direct evidence of diseases, animal and human migrations, diet, sanitation habits, etc. (Dittmar, 2009). These are also hard to determine microscopically because they are rarely preserved (particularly endoparasites). Parasites are more commonly found in feces or hair, and nowadays their presence and composition are more effectively determined by DNA analyses.

Molecular analysis

Emerging molecular methodologies provide powerful new tools, successfully used across the various subfields of paleodemographic research. These are not infallible; on the contrary, their high power of discrimination can be their main setback, because the sensitivity of the techniques can amplify any contamination. Nevertheless, molecular methods promise to fill important gaps in paleodemographic studies. This review considers only two of the current molecular approaches, isotope and DNA analysis of ancient human remains (ancient DNA or aDNA), which are the most widely used molecular techniques in bioarchaeology.



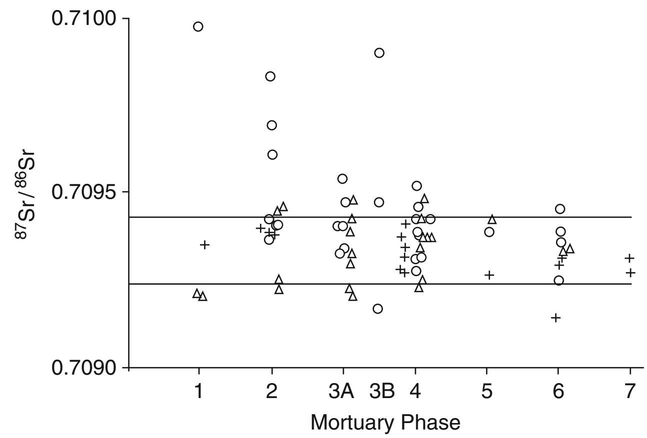
Paleodemography: Methods and Recent Advances, Figure 3 A comparison of dental microwear. (**a**) Gray-cheeked mangabey (*Lophocebus albigena*) of Central Africa; (**b**) *H. erectus*; (**c**) *H. habilis*; (**d**) *Gorilla gorilla*. Note the size and number of pits in these four species. Larger pits (as in **a** and **b**) are indicative of a diet composed predominantly of hard but brittle foods, while smaller pits and more striations (as in **c** and **d**) are suggestive of a diet comprising mostly tough leaves or stems (Reproduced from (Ungar et al., 2006)).

Isotope analysis

Many common elements (such as carbon, hydrogen, strontium) occur with different atomic masses, and these variants are called isotopes. For example, carbon (C) has three naturally occurring forms, ^{12}C, ^{13}C, and ^{14}C, whereas nitrogen (N) has two, ^{14}N and ^{15}N. Isotopic signatures are the ratio of stable isotopes in a particular material. Signatures of light isotopes, such as C and N, are mainly influenced by reaction rates (the speed at which isotopes form and break chemical bonds), whereas that of heavy isotopes, such as strontium (Sr), are primarily influenced by the substrate (the source of the isotope, e.g., foods or minerals in the water consumed by the organism) (Schoeninger, 1995). Isotopic signatures can be studied in a variety of archaeological material such as bone and dentine collagen, bone mineral and enamel, hair, nails, organic residues in artifacts (pottery, stone tools, etc.), and coprolites, providing information about different processes. For example, enamel and dentine are formed in childhood and adolescence and do not remodel during adulthood; thus their isotopic signatures reflect these early periods and can determine where people may have been born and spent most of their childhood. Conversely, bone has a regular turnover, and isotopic signatures reflect a -long-term average that can inform deductions about diet and behavior. Hair has a very rapid turnover, and so its isotope signatures may reflect the environment at the time of death, whereas isotopes in coprolites can provide evidence of foods consumed in a particular season.

The largest source of carbon isotope variability occurs in plants and primary consumers (herbivores). Land plants fix atmospheric ^{12}C with differing efficiency depending on the enzymatic pathway used for carboxylation, thus resulting in different $^{13}C/^{12}C$ ratios. These ratios are then reflected in the tissues of the consumers (animals and humans) and are therefore indicative of food consumption (Lee-Thorpe, 2008). The main source of $^{13}C/^{12}C$ in archaeological material is bone collagen and enamel, with the former used primarily for dietary determinations. $^{13}C/^{12}C$ signatures have been particularly useful in understanding patterns of resource utilization in hominin species, likely associated with adaptations for a more versatile subsistence strategy that gave them an advantage during climatic changes and habitat diversification in the late Pliocene (Lee-Thorpe, 2008).

Nitrogen enters the food chain either through bacterial degradation of organic material in the soil or through nitrogen-fixing bacteria in root nodules (e.g., legumes). These plants have higher relative content of ^{15}N. There is a stepwise enrichment of ^{15}N in each trophic level, probably due to inefficient excretion of ^{15}N (Schoeninger, 1995). Therefore, the higher an organism is in the food chain, the higher their $^{15}N/^{14}N$ ratio, with carnivores (secondary and tertiary consumers) presenting the highest values. Marine organisms have higher ^{15}N content than terrestrial organisms, which can be reflected in the isotopic signatures of individuals with a predominantly marine diet.



Paleodemography: Methods and Recent Advances, Figure 4 Sr signatures from remains of seven mortuary phases spanning 500 years at the archaeological site of Khok Phanom Di (Thailand). *Horizontal lines* delimit the local Sr values, which lie between 0.7092 and 0.7094. Note that the early phases are characterized by overrepresentation of nonlocal women (*circles*), who show ratios well above 0.7095, whereas men (*triangles*) and *crosses* (infants) are mostly local, suggesting a pattern of patrilocality at this site (Redrawn from (Bentley et al., 2007)).

Strontium differs from nitrogen and carbon in that it is a highly stable heavy isotope, with a signature that reflects its source. Different rocks contain different levels of ^{87}Sr which enters the food chain through the water and rock minerals absorbed by plants. There is no stepwise enrichment of ^{87}Sr; hence the relative $^{87}Sr/^{86}Sr$ ratios in the skeleton primarily reflect the geographic environment from which the organism has taken the Sr (groundwater and/or local vegetation), therefore making it useful for geographic provenancing. As skeletal tissue remodels through life, $^{87}Sr/^{86}Sr$ signatures reflect a lifetime average of the individual's geographic residence (Figure 4). Tooth enamel, which forms during infancy, does not remodel; hence $^{87}Sr/^{86}Sr$ values reflect the geographic environment during childhood.

aDNA analysis

Methodological advances in the last decades have enabled the successful recovery of DNA from preserved skeletal remains, plants and animals, mummified tissue, coprolites, hair, and even sediments and permafrost. The extraction of aDNA (or ancient DNA) from bioarchaeological material involves the use of invasive techniques, so careful cost-benefit analysis must always be conducted to avoid the unnecessary destruction of unique material. It is generally accepted that DNA preservation is considerably poorer in temperate environments compared with very cold regions; thus, the chances of successfully obtaining DNA sequences from specimens from these regions are considerably reduced and would require more extensive destruction, as a larger sample would be needed to achieve successful DNA extraction.

The advent of next-generation sequencing (NGS) has contributed further, enabling us to overcome some of the early limitations of aDNA research, namely, the small amount of DNA surviving in bioarchaeological material, but it has also brought fresh difficulties (e.g., the high potential for contamination with DNA from modern sources). Contamination with modern DNA has led to some spectacular claims, famously the multiregional origin of modern humans based on putatively aDNA sequences from the 50,000-year-old skeleton from Lake Mungo, Australia (Adcock et al., 2001) and, more recently, the claim that up to 30 % of the human genome is shared with Neanderthals, thus supporting the view that modern humans and Neanderthals interbred (Green et al., 2006). Nowadays, stringent protocols to avoid contamination are in place and, in most cases, are a prerequisite for publication (Gilbert et al., 2005).

Despite the issues of preservation and contamination, aDNA has extraordinary potential to elucidate past population history, probably more than any other methodology. The distribution of human genetic variation shows a striking geographic structure at the continental level, and provided that sufficient DNA variants are tested, it is possible to infer ancestry and ethnic relatedness with a high degree of accuracy. However, this is less true at the microgeographic scale, as migrations and admixture at the local level tend to blur genetic signatures. Therefore, genetic analyses of human remains can be valuable for inferring broad patterns of migrations.

aDNA analysis is often the only way to elucidate phylogenetic relationships between extant and extinct groups, particularly when osteological material is insufficient for morphological studies. Two genetic studies conducted on a phalanx from an unknown female hominin group discovered at the Denisova Cave in Southern Siberia revealed that the bone belonged to a new hominin group that shares a common ancestor with modern humans and Neanderthals and diverged about 1 million years ago, thus suggesting a migration out of Africa different from that of the ancestors of modern humans and Neanderthals (Krause et al., 2010; Reich et al., 2010). The finger bone had been found in a stratum containing both Middle and Upper Paleolithic elements and had been radiocarbon dated to approximately 41,000 years ago, but both the morphology and the stratigraphy were difficult to interpret.

Some current topics in paleodemography

The peopling of the Americas

America is one of the last frontiers of human dispersal out of Africa, but the details of the initial settlement are poorly understood. Competing hypotheses regarding the routes and times of human dispersals throughout the continent have been discussed, each with broad implications for the evolution of human diversity over the last 15,000 years.

Early archaeological evidence from a number of sites in North America pointed to the Clovis culture as the first inhabitants of the continent, approximately 11,000 years ago (or 11 ka) (Waters and Stafford, 2007). Several sites in South America consistently yield radiocarbon dates just prior to 11 ka, proving the presence of humans in the Southern Cone before the first North American Clovis sites (Steele and Politis, 2009). Evidence of pre-Clovis settlement is not limited to South America; radiocarbon dating and DNA evidence from a human coprolite in the USA also suggested human presence in North America before 12 ka (Gilbert et al., 2008). The expansion of the Clovis culture, therefore, was probably the result of a second migration that may have erased the signature of the first dispersal from the archaeological record (Fiedel, 2000). This two-wave scenario is now supported by genetic data (Fagundes et al., 2008; Hellenthal et al., 2008; Perego et al., 2009), analyses of human cranial morphology (Hubbe et al., 2010), and radiocarbon dating of charcoal and cut-marked animal bones (Steele and Politis, 2009).

The last glacial period exposed a land bridge between Northeast Asia and Alaska (Beringia), allowing the first Americans to move eastward from Asia. The dispersal may have halted in Beringia, where the gene pool accumulated American-specific DNA mutations (Tamm et al., 2007). The Beringian incubation occurred around 23–19 ka (Fagundes et al., 2008) or 21–18 ka (Achilli et al., 2008).

After the glacial maximum (18 ka), only two routes from Beringia to the Americas appear possible: (1) an early coastal route along the Pacific coast or (2) a later inland corridor between continental glaciers. Mitochondrial DNA (mtDNA) evidence indicates a first migration along the coast approximately 18–15 ka (Fagundes et al., 2008) and a later migration through the newly opened ice-free corridor. The Pacific coastal route hypothesis remained controversial due to a lack of archaeological evidence until the discovery of several drowned archaeological sites just below the Pacific shoreline, radiocarbon dated to 13–9.5 ka (Fedje and Christensen, 1999).

Neolithic expansions and the beginnings of agriculture

The beginning of the Holocene was marked by profound climatic changes leading to the spread of plants and animals, sea level rise, reshaping of landmasses, etc., that provided new opportunities for human adaptation. The human response to ecological change was probably the transition from nomadism to sedentism and the development of farming. This then allowed population growth and expansion, both demic and cultural.

It has long been debated whether the spread of agriculture to Europe from its center of origin in Southwest Asia was merely a cultural process or was mediated by significant migrations. Early studies suggested a clinal distribution of human blood group frequencies, explained in terms of demic diffusion from the Near East (Ammerman and Cavalli-Sforza, 1984), whereas studies of extant European mtDNA lineages (reflecting their maternal ancestry) suggested a predominant Paleolithic component in the gene pool of Europeans, thus dismissing any significant contribution from Neolithic migrations (Richards et al., 2000; Richards and Macaulay, 2000). Later studies of mtDNA from ancient remains showed different lineage frequencies between Neolithic and modern Europeans, supporting the idea of a limited contribution of Neolithic farmers to the genetic pool of extant Europeans. However, a recent study on craniometric diversity suggested that Mesolithic and Neolithic populations are substantially differentiated and skull variation best fits a model of continuous dispersal from Southwest Asia (Pinhasi and von Cramon-Taubadel, 2009). Studies of European Y chromosomes (reflecting the paternal ancestry) have also suggested a significant contribution of Near Eastern lineages and stressed the unique role of male-mediated migrations during the Neolithic transition (Balaresque et al., 2010). Moreover, Sr isotopic signatures paint a more complex picture of patrilocality and indigenous adoption of agriculture following a single Neolithic colonization (Bentley et al., 2002). These studies illustrate both the complexity of European paleodemography and the benefits of an integrated multidisciplinary approach in gaining a fuller picture of the past.

Summary

Few fields of enquiry match the recent expansion and progress of paleodemographic studies, made possible by methodological advances and the contribution of emergent disciplines, such as aDNA, that have turned the field into a truly multidisciplinary endeavor. Despite the inherent limitations of preservation and contamination, bioarchaeological material is more than ever open to enquiry, and there is a growing sense that in years to come, new breakthroughs will fill important gaps in the understanding of our human past.

Bibliography

Achilli, A., Perego, U. A., Bravi, C. M., Coble, M. D., Kong, Q.-P., Woodward, S. R., Salas, A., Torroni, A., and Bandelt, H.-J., 2008. The phylogeny of the four Pan-American mtDNA haplogroups: implications for evolutionary and disease studies. *PLoS One*, **3**(3), e1764.

Adcock, G. J., Dennis, E. S., Easteal, S., Huttley, G. A., Jermiin, L. S., Peacock, W. J., and Thorne, A., 2001. Mitochondrial DNA sequences in ancient Australians: implications for modern human origins. *Proceedings of the National Academy of Sciences*, **98**(2), 537–542.

Ammerman, A. J., and Cavalli-Sforza, L. L., 1984. *The Neolithic Transition and the Genetics of Populations in Europe*. Princeton: Princeton University Press.

Balaresque, P., Bowden, G. R., Adams, S. M., Leung, H.-Y., King, T. E., Rosser, Z. H., Goodwin, J., Moisan, J.-P., Richard, C., Millward, A., Demaine, A. G., Barbujani, G., Previderè, C., Wilson, I. J., Tyler-Smith, C., and Jobling, M. A., 2010. A predominantly Neolithic origin for European paternal lineages. *PLoS Biology*, **8**(1), e1000285.

Bengtsson, C. F., Olsen, M. E., Brandt, L. Ø., Bertelsen, M. F., Willerslev, E., Tobin, D. J., Wilson, A. S., and Gilbert, M. T. P., 2011. DNA from keratinous tissue. Part I: hair and nail. *Annals of Anatomy – Anatomischer Anzeiger*, **194**(1), 17–25.

Bentley, R. A., Price, T. D., Lüning, J., Gronenborn, D., Wahl, J., and Fullagar, P. D., 2002. Prehistoric migration in Europe: strontium isotope analysis of early Neolithic skeletons. *Current Anthropology*, **43**(5), 799–804.

Bentley, R. A., Tayles, N., Higham, C. F. W., Macpherson, C., and Atkinson, T. C., 2007. Shifting gender relations at Khok Phanom Di, Thailand: isotopic evidence from the skeletons. *Current Anthropology*, **48**(2), 301–314.

Bernal, V., Perez, S. I., and Gonzalez, P. N., 2006. Variation and causal factors of craniofacial robusticity in Patagonian hunter-gatherers from late Holocene. *American Journal of Human Biology*, **18**(6), 748–765.

Bryant, V. M., and Dean, G. W., 2006. Archaeological coprolite science: the legacy of Eric O. Callen (1912–1970). *Palaeogeography, Palaeoclimatology, Palaeoecology*, **237**(1), 51–66.

Cleghorn, B. M., Christie, W. H., and Dong, C. C. S., 2007. The root and root canal morphology of the human mandibular first premolar: a literature review. *Journal of Endodontics*, **33**(7), 509–516.

Collins, M. J., Nielsen-Marsh, C. M., Hiller, J., Smith, C. I., Roberts, J. P., Prigodich, R. V., Wess, T. J., Csapò, J., Millard, A. R., and Turner-Walker, G., 2002. The survival of organic matter in bone: a review. *Archaeometry*, **44**(3), 383–394.

DeGaetano, D. H., Kempton, J. B., and Rowe, W. F., 1992. Fungal tunneling of hair from a buried body. *Journal of Forensic Science*, **37**(4), 1048–1054.

Dittmar, K., 2009. Old parasites for a new world: the future of paleoparasitological research. A review. *Journal of Parasitology*, **95**(2), 365–371.

Donoghue, H. D., Hershkovitz, I., Minnikin, D. E., Besra, G. S., Lee, O. Y.-C., Galili, E., Greenblatt, C. L., Lemma, E., Spigelman, M., and Bar-Gal, G. K., 2009. Biomolecular archaeology of ancient tuberculosis: response to "Deficiencies and challenges in the study of ancient tuberculosis DNA" by Wilbur et al. (2009). *Journal of Archaeological Science*, **36**(12), 2797–2804.

Fagundes, N. J. R., Kanitz, R., and Bonatto, S. L., 2008. A reevaluation of the Native American mtDNA genome diversity and its bearing on the models of early colonization of Beringia. *PLoS One*, **3**(9), e3157.

Fedje, D. W., and Christensen, T., 1999. Modeling paleoshorelines and locating Early Holocene coastal sites in Haida Gwaii. *American Antiquity*, **64**(4), 635–652.

Fiedel, S. J., 2000. The peopling of the new world: present evidence, new theories, and future directions. *Journal of Archaeological Research*, **8**(1), 39–103.

Franklin, D., 2010. Forensic age estimation in human skeletal remains: current concepts and future directions. *Legal Medicine*, **12**(1), 1–7.

Gilbert, M. T. P., Bandelt, H.-J., Hofreiter, M., and Barnes, I., 2005. Assessing ancient DNA studies. *TRENDS in Ecology and Evolution*, **20**(10), 541–544.

Gilbert, M. T. P., Jenkins, D. L., Götherström, A., Naveran, N., Sanchez, J. J., Hofreiter, M., Thomsen, P. F., Binladen, J., Higham, T. F. G., Yohe, R. M., II, Parr, R., Cummings, L. S., and Willerslev, E., 2008. DNA from Pre-Clovis human coprolites in Oregon, North America. *Science*, **320**(5877), 786–789.

Goldberg, P., Berna, F., and Macphail, R. I., 2009. Comment on "DNA from Pre-Clovis human coprolites in Oregon, North America". *Science*, **325**(5937), 148.

Green, R. E., Krause, J., Ptak, S. E., Briggs, A. W., Ronan, M. T., Simons, J. F., Du, L., Egholm, M., Rothberg, J. M., Paunovic, M., and Pääbo, S., 2006. Analysis of one million base pairs of Neanderthal DNA. *Nature*, **444**(7117), 330–336.

Hedges, R. E. M., 2002. Bone diagenesis: an overview of processes. *Archaeometry*, **44**(3), 319–328.

Hellenthal, G., Auton, A., and Falush, D., 2008. Inferring human colonization history using a copying model. *PLoS Genetics*, **4**(6), e1000078.

Hubbard, A. R., Guatelli-Steinberg, D., and Irish, J. D., 2015. Do nuclear DNA and dental nonmetric data produce similar reconstructions of regional population history? An example from modern coastal Kenya. *American Journal of Physical Anthropology*, doi:10.1002/ajpa.22714.

Hubbe, M., Neves, W. A., and Harvati, K., 2010. Testing evolutionary and dispersion scenarios for the settlement of the New World. *PLoS One*, **5**(6), e11105.

Ishida, H., Hanihara, T., Kondo, O., and Fukumine, T., 2009. Craniometric divergence history of the Japanese populations. *Anthropological Science, Journal of the Anthropological Society of Nippon*, **117**(3), 147–156.

Jans, M. M. E., Nielsen-Marsh, C. M., Smith, C. I., Collins, M. J., and Kars, H., 2004. Characterisation of microbial attack on archaeological bone. *Journal of Archaeological Science*, **31**(1), 87–95.

Katzmarzyk, P. T., and Leonard, W. R., 1998. Climatic influences on human body size and proportions: ecological adaptations and secular trends. *American Journal of Physical Anthropology*, **106**(4), 483–503.

Krause, J., Fu, Q., Good, J. M., Viola, B., Shunkov, M. V., Derevianko, A. P., and Pääbo, S., 2010. The complete mitochondrial DNA genome of an unknown hominin from southern Siberia. *Nature*, **464**(7290), 894–897.

Kunert, J., 1989. Growth of keratinolytic and non-keratinolytic fungi on human hairs. A physiological study. *Acta Universitatis Palackianae Olomucensis Facultatis Medicae*, **122**, 25–38.

Lahr, M. M., 1995. Patterns of modern human diversification: implications for Amerindian origins. Yearbook of physical anthropology. *American Journal of Physical Anthropology*, **38**(Suppl S2), 163–198.

Lee-Thorpe, J. A., 2008. On isotopes and old bones. *Archaeometry*, **50**(6), 925–950.

Meindl, R. S., and Russell, K. F., 1998. Recent advances in method and theory in paleodemography. *Annual Review of Anthropology*, **27**, 375–399.

Özer, İ., and Katayama, K., 2008. Sex determination using the femur in an ancient Japanese population. *Collegium Antropologicum*, **32**(1), 67–72.

Perego, U. A., Achilli, A., Angerhofer, N., Accetturo, M., Pala, M., Olivieri, A., Hooshiar Kashani, B., Ritchie, K. H., Scozzari, R., Kong, Q. P., Myres, N. M., Salas, A., Semino, O., Bandelt, H. J., Woodward, S. R., and Torroni, A., 2009. Distinctive Paleo-Indian migration routes from Beringia marked by two rare mtDNA haplogroups. *Current Biology*, **19**(1), 1–8.

Perez, S. I., Bernal, V., and Gonzalez, P. N., 2007. Morphological differentiation of aboriginal human populations from Tierra del Fuego (Patagonia): implications for South American peopling. *American Journal of Physical Anthropology*, **133**(4), 1067–1079.

Perez, S. I., Bernal, V., Gonzalez, P. N., Sardi, M., and Politis, G. G., 2009. Discrepancy between cranial and DNA data of early Americans: implications for American peopling. *PLoS One*, **4**(5), e5746.

Pinhasi, R., and von Cramon-Taubadel, N., 2009. Craniometric data supports demic diffusion model for the spread of agriculture into Europe. *PLoS One*, **4**(8), e6747.

Reich, D., Green, R. E., Kircher, M., Krause, J., Patterson, N., Durand, E. Y., Viola, B., Briggs, A. W., Stenzel, U., Johnson, P. L. F., Maricic, T., Good, J. M., Marques-Bonet, T., Alkan, C., Fu, Q., Mallick, S., Li, H., Meyer, M., Eichler, E. E., Stoneking, M., Richards, M., Talamo, S., Shunkov, M. V., Derevianko, A. P., Hublin, J.-J., Kelso, J., Slatkin, M., and Pääbo, S., 2010. Genetic history of an archaic hominin group from Denisova Cave in Siberia. *Nature*, **468**(7327), 1053–1060.

Reinhard, K. J., and Bryant, V. M., Jr., 1992. Coprolite analysis: a biological perspective on archaeology. In Schiffer, M. B. (ed.), *Advances in Archaeological Method and Theory*. Tucson: University of Arizona Press, Vol. 4, pp. 245–288.

Richards, M. B., and Macaulay, V., 2000. Genetic data and the colonization of Europe: genealogies and founders. In Renfrew, C., and Boyle, K. V. (eds.), *Archaeogenetics: DNA and the Population Prehistory of Europe*. Cambridge: McDonald Institute for Archaeological Research, pp. 139–151.

Richards, M., Macaulay, V., Hickey, E., Vega, E., Sykes, B., Guida, V., Rengo, C., Sellitto, D., Cruciani, F., Kivisild, T., Villems, R., Thomas, M., Rychkov, S., Rychkov, O., Rychkov, Y., Gölge, M., Dimitrov, D., Hill, E., Bradley, D., Romano, V., Calì, F., Vona, G., Demaine, A., Papiha, S., Triantaphyllidis, C., Stefanescu, G., Hatina, J., Belledi, M., Di Rienzo, A., Novelletto, A., Oppenheim, A., Nørby, S., Al-Zaheri, N., Santachiara-Benerecetti, S., Scozari, R., Torroni, A., and Bandelt, H. J., 2000. Tracing European founder lineages in the near eastern mtDNA pool. *American Journal of Human Genetics*, **67**(5), 1251–1276.

Scheuer, L., 2002. Application of osteology to forensic medicine. *Clinical Anatomy*, **15**(4), 297–312.

Schoeninger, M. J., 1995. Stable isotope studies in human evolution. *Evolutionary Anthropology*, **4**(3), 83–98.

Slice, D. E., 2007. Geometric morphometrics. *Annual Review of Anthropology*, **36**, 261–281.

Steele, J., and Politis, G., 2009. AMS^{14}C dating of early human occupation of southern South America. *Journal of Archaeological Science*, **36**(2), 419–429.

Tamm, E., Kivisild, T., Reidla, M., Metspalu, M., Smith, D. G., Mulligan, C. J., Bravi, C. M., Rickards, O., Martinez-Labarga, C., Khusnutdinova, E. K., Fedorova, S. A., Golubenko, M. V., Stepanov, V. A., Gubina, M. A., Zhadanov, S. I., Ossipova, L. P., Damba, L., Voevoda, M. I., Dipierri, J. E., Villems, R., and Malhi, R. S., 2007. Beringian standstill and spread of Native American founders. *PLoS One*, **2**(9), e829.

Taylor, R. E., Hare, P. E., Prior, C. A., Kirner, D. L., Wan, L., and Burky, R. B., 1995. Radiocarbon dating of biochemically characterized hair. *Radiocarbon*, **37**(2), 319–330.

Temple, D. H., Auerbach, B. M., Nakatsukasa, M., Sciulli, P. W., and Larsen, C. S., 2008. Variation in limb proportions between Jomon foragers and Yayoi agriculturalists from prehistoric Japan. *American Journal of Physical Anthropology*, **137**(2), 164–174.

Ungar, P. S., Grine, F. E., and Teaford, M. F., 2006. Diet in early *Homo*: a review of the evidence and a new model of adaptive versatility. *Annual Review of Anthropology*, **35**, 209–228.

Waters, M. R., and Stafford, T. W., Jr., 2007. Redefining the age of Clovis: implications for the peopling of the Americas. *Science*, **315**(5815), 1122–1126.

Wilson, A. S., Dodson, H. I., Janaway, R. C., Pollard, A. M., and Tobin, D. J., 2007. Selective biodegradation in hair shafts derived from archaeological, forensic and experimental contexts. *British Journal of Dermatology*, **157**(3), 450–457.

Wilson, A. S., Dodson, H. I., Janaway, R. C., Pollard, A. M., and Tobin, D. J., 2010. Evaluating histological methods for assessing hair fibre degradation. *Archaeometry*, **52**(3), 467–481.

PALEODIET

Judith Sealy
Department of Archaeology, University of Cape Town, Rondebosch, Cape Town, South Africa

Synonyms

Paleonutrition

Definition

Ancient foodways reconstructed using various avenues of archaeological evidence, including artifacts, anatomical features, and the chemical composition of remains.

Introduction

In recent decades, studies of human and animal paleodiet have become increasingly important across a timescale ranging from the recent past (forensics and historical archaeology) to deep time (paleontology). This entry will summarize biogeochemical approaches to reconstructing paleodiet. Other approaches include studies of tooth shape, size, structure, and wear (e.g., Ungar, 2011, and references therein) and identification of food refuse from living sites, especially in archaeology. The best understanding of paleodiet usually comes from combining as many different types of evidence as possible.

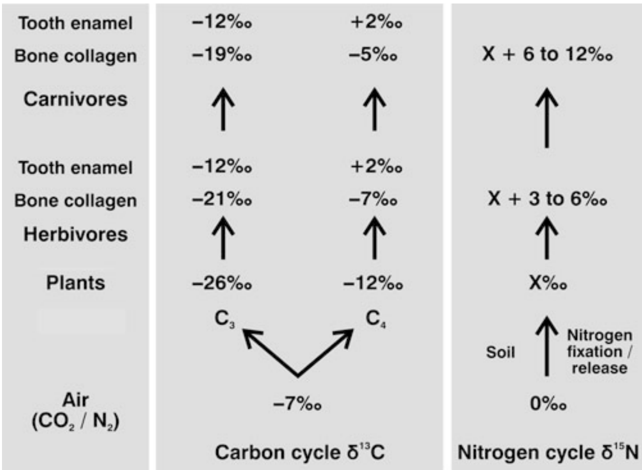
Basic principles

Biogeochemical studies of paleodiet involve stable isotope and/or trace element measurements of preserved tissues in order to reconstruct diet during life. Stable isotope approaches are based on the ratio of the (less common) heavier isotope to the (more common) lighter isotope, for example, $^{13}C/^{12}C$. While the amount of carbon and its structural position within any living tissue is tightly controlled, the ratio of ^{13}C to ^{12}C varies according to the diet consumed in life. For successful biogeochemical studies, there are two necessary preconditions: (i) the isotopes or trace elements in question must be differentially distributed across different categories of foods in ways that we understand, and (ii) the tissues being analyzed must retain their original composition. The first criterion is relatively well met for stable carbon isotopes ($^{13}C/^{12}C$), rather less so for $^{15}N/^{14}N$, $^{18}O/^{16}O$ (in paleodiet studies), $^{34}S/^{32}S$, and $^{2}H/^{1}H$. Trace element distributions in nature are very variable; for paleodietary purposes, the most useful are probably Sr and Ba, which may substitute for Ca in the mineral lattices of calcified tissues such as bones and teeth (Brown, 1974; Schoeninger, 1979; Sillen and Kavanagh, 1982; Burton et al., 1999).

Stable isotope ratios are reported as δ values relative to an internationally accepted standard: $\delta^{H}X = (R_{sample}/R_{reference} - 1) \times 1000$ where H is the mass of the heavier isotope, X may be the elements C, N, O, H, S, etc., and R is the ratio $^{13}C/^{12}C$, $^{15}N/^{14}N$, $^{18}O/^{16}O$, $^{2}H/^{1}H$ (also referred to as D/H, or deuterium/hydrogen), or $^{34}S/^{32}S$. The units are parts per thousand or per mille (‰). The standard material for carbon isotopes is the marine limestone PDB – or the Pee Dee Belemnite, a Cretaceous deposit in South Carolina composed largely of the fossil cephalopod *Belemnitella americana*. For oxygen and hydrogen isotopes, the standard may be PDB or Standard Mean Ocean Water (SMOW). For nitrogen isotopes, the international standard is atmospheric nitrogen, or Ambient Inhalable Reservoir (AIR), and for sulfur isotopes it is the iron sulfide troilite of the Canyon Diablo meteorites (CDT), which are fragments of the meteor that created the Barringer Crater in Arizona. Negative values show that the sample contains less of the heavy isotope than does the standard, while positive values indicate more of the heavy isotope (Sharp, 2007; Hoefs, 2009).

Isotopic discrimination during photosynthesis forms the basis of variation in the proportions of carbon isotopes in living organisms. Atmospheric carbon dioxide contains mostly $^{12}CO_2$, with approximately 1 % $^{13}CO_2$. $\delta^{13}C_{atmosphere}$ in preindustrial times was approximately −6.5 ‰; it is currently around −8 ‰ and becoming more negative due to the combustion of fossil fuels (Friedli et al., 1986; Trudinger et al., 2002). $^{12}CO_2$ molecules dissolve more readily in moisture on the surfaces of leaves and diffuse more easily through plant stomata than larger, heavier $^{13}CO_2$. In addition, the photosynthetic enzyme RUBISCO strongly favors $^{12}CO_2$, leading to the formation of plant tissue that has more ^{12}C and less ^{13}C than atmospheric carbon dioxide; such a shift in isotope ratio is called "fractionation." Plants that photosynthesize using the C_3 or Calvin-Benson pathway have $\delta^{13}C$ values of about −27 ‰, those using the C_4 or Hatch-Slack pathway have values around −13 ‰ (O'Leary, 1988; Cerling et al., 1997). Most C_4 plants are tropical grasses, so low-latitude grasslands are C_4-dominated ecosystems. The economically important tropical grasses maize, sugarcane, sorghum, and millet are also C_4, and when introduced as crop plants into areas that are otherwise C_3, their contribution to the food chain can readily be identified (Vogel and van der Merwe, 1977; van der Merwe and Vogel, 1978; Buikstra and Milner, 1991). Plants in temperate regions and high-altitude environments are C_3, as are wheat, barley, oats, rice, nearly all trees and shrubs, and fruits and vegetables. (There are a few exceptions, particularly succulent plants such as prickly pears and pineapples, but these are sufficiently unusual that they need not receive detailed discussion here.)

The isotopic composition of animals and humans derives from the food they have eaten. There is some further partitioning of isotopes within the body, for example, much ingested ^{12}C is respired as CO_2 while a relatively greater proportion of ^{13}C is used to synthesize muscle, bones, and teeth. Figure 1 shows some average values as one moves along a food chain. Note that different body tissues have different $\delta^{13}C$ values: the two tissues most frequently used in paleodietary studies are bone collagen and tooth enamel.



Paleodiet, Figure 1 Approximate values for $\delta^{13}C$ and $\delta^{15}N$ in typical food chains. Note that the concentration and isotope ratio of atmospheric CO_2 depends upon the global carbon cycle. Values at the Last Glacial Maximum (about 26.5 to 19 ka) differed from those of the Holocene (Leuenberger et al., 1992) with more substantial shifts in deeper time (Zachos et al., 2001). Adapted from Figure 3 in Lee-Thorp and Sponheimer (2006), using a value of +14‰ for the isotopic spacing between diet and herbivore tooth enamel (Cerling and Harris, 1999; Passey et al., 2005). $\delta^{15}N$ values of plants are very variable (depending on nitrogen in the soil), and hence they are represented by X.

The same basic principles apply to other stable isotopes: in most chemical reactions the lighter isotope is preferred for energetic reasons, leading to isotopic fractionation. The degree of fractionation is the highest for $^2H/^1H$, where the mass difference between the isotope pair is greatest. $\delta^{15}N$ increases by 3–6‰ in consumers compared with their food, making it useful as a trophic level indicator (Schoeninger et al., 1983; Hedges and Reynard, 2007). $\delta^{34}S$ shows little stepwise fractionation along food chains, but there are significant differences between marine and most terrestrial and/or freshwater environments. Hoefs (2009) and Sharp (2007) provide excellent overviews of the distributions of stable isotopes in various geochemical reservoirs. Fry (2006) and chapters in Michener and Lajtha (2007), especially Koch (2007), discuss stable isotopes in life sciences and ecology.

Issues to keep in mind

Much early paleodietary work (in the 1970s and 1980s) attempted to use trace element concentrations in bones and teeth to reconstruct foods consumed in life. Researchers came to realize, however, that the distribution of many trace elements is not as predictable as was initially thought, and that metabolic control over which components of food are incorporated into body tissues frequently makes it difficult or impossible to identify meaningful paleodietary signals in trace element profiles of calcified tissues. Postdepositional contamination or "diagenesis" is also a serious problem, especially in bone and dentin. Tooth enamel, which is a much denser material, is less affected by postdepositional processes. In certain situations, diagenetic trace element signals can contribute valuable information, for example, to distinguish components of mixed ex situ fossil assemblages with different taphonomic histories.

Diagenesis can be a problem in stable isotope studies, too. In relatively well-preserved material, the analytical tissue of choice is usually collagen, the major structural protein of bone. Collagen contains carbon and nitrogen, enabling measurement of $\delta^{13}C$ and $\delta^{15}N$, also $\delta^{34}S$, $\delta^{18}O$, and $\delta^{2}H$ (although the last three have been much less studied). Collagen extraction has been extensively researched in relation to radiocarbon dating, which is much more sensitive to contamination than stable isotope analysis. Collagen molecules consist of three protein chains wound together in a triple helix; if this structure is preserved, isotopic integrity is likely to have been maintained (van Klinken, 1999). In old or poorly preserved materials, especially those from tropical environments, collagen may have decayed. It is possible to measure $\delta^{13}C$ and $\delta^{18}O$ in the small amounts of carbonate incorporated into bone apatite, but diagenesis in bone apatite can be difficult to detect and mitigate. In the absence of collagen, most researchers now prefer to analyze tooth enamel (composed mostly of apatite), which can preserve its original ("biogenic") composition over millions of years (Ayliffe et al., 1994; Wang and Cerling, 1994; Koch et al., 1997; Lee-Thorp, 2002, 2008).

Collagen is a protein, and carbon atoms in collagen tend to derive mainly from protein foods in the diet. $\delta^{13}C_{collagen}$ therefore tracks primarily protein foods, while dietary fats and carbohydrates are under-represented (Ambrose and Norr, 1993; Tieszen and Fagre, 1993; Howland et al., 2003; Jim et al., 2004). Carbonate in apatite, on the other hand, is formed from blood bicarbonate. Since most ingested carbon is converted into blood bicarbonate, $\delta^{13}C_{bone\ apatite}$ is a better indicator of total diet than $\delta^{13}C_{collagen}$, as long as the diagenetic issues mentioned above can be dealt with. Analysis of both $\delta^{13}C_{collagen}$ and $\delta^{13}C_{bone\ apatite}$ can reveal added dimensions of foods consumed, especially if diets were isotopically heterogeneous. Ambrose et al. (1997) showed that in human skeletons from the Marianas, $\delta^{13}C_{bone\ apatite}$ reflected consumption of sugarcane that was invisible in $\delta^{13}C_{collagen}$. Bone apatite and tooth enamel both derive from blood bicarbonate, and until recently, most studies have assumed that $\delta^{13}C_{bone\ apatite}$ and $\delta^{13}C_{tooth\ enamel}$ are equivalent. We now know that this is not the case (Warinner and Tuross, 2009; Loftus and Sealy, 2012), but the reasons are not obvious. The problem is most acute for $\delta^{13}C$ since carbon may originate from different nutrients, whereas in higher organisms, nitrogen is incorporated mostly from protein. Researchers have not yet begun to consider this issue for other isotopes.

One of the original goals of isotopic and trace element studies of diet was to achieve precise quantitative reconstructions of foods eaten. Ecologists use mixing models for this purpose, whereby n isotopic indicators in the tissues of a consumer are used to calculate proportions of n + 1 isotopically different food sources (Phillips, 2001; Phillips and Koch, 2002; Phillips et al., 2005). For example, measurement of $\delta^{13}C$ and $\delta^{15}N$ in bone collagen can enable three categories of foods to be distinguished. This approach assumes that all foods contribute equally to the tissues being analyzed: an assumption that we know is not valid for carbon. In some situations, this may not matter much; in others (e.g., Ambrose et al., 1997), it renders this approach invalid.

It should be remembered that the isotopic and trace element composition of a tissue reflect diet during the period over which that tissue was laid down. Tooth enamel forms early in life, and once formed, it is metabolically inert. Bone, on the other hand, continues to grow and remodel throughout life. Analyses of tooth enamel and bone therefore track diet at different stages of life, a phenomenon that can be put to work to trace dietary life histories of individuals (Sealy et al., 1995; Cox et al., 2001; Price et al., 2001, 2006). Serial analyses of tooth enamel record life events during the period of formation of that tooth (Wright and Schwarcz, 1998; Balasse, 2002; Sponheimer et al., 2006). If soft tissues are also preserved, even more detailed reconstructions are possible (Müller et al., 2003; Richards et al., 2007; Meier-Augenstein and Fraser, 2008; see also Stott et al., 1999).

Some applications

Analysis of carbon isotopes in paleosols and in the tooth enamel of fossil grazers has enabled some elegant reconstructions of past ecosystems, including the demonstration that the C_4 grasslands that today dominate many low-latitude regions of the world developed only in the late Miocene, ca. 8–6 mya (Cerling et al., 1993; Wang et al., 1994). We do not yet fully understand the reasons for this major worldwide ecological transformation, but these are likely to have been complex, involving geological, ecological, and phylogenetic aspects (Edwards et al., 2010). In Australia, Miller et al. (2005) found that $\delta^{13}C$ values of ancient eggshells indicated major environmental change between 50 and 45 ka. These authors suggest that the first humans in Australia burned the landscape, changing the vegetation from a patchwork of different plant communities, including significant quantities of C_4 grasses, to fire-adapted scrub like that of today.

Stable isotope analyses of fossil tooth enamel have been used to reconstruct the diets of extinct species, including fossil human ancestors (Sponheimer et al., 2006; Lee-Thorp and Sponheimer, 2006; Lee-Thorp, 2008; Cerling et al., 2011; Ungar and Sponheimer, 2011). This work has significantly changed our understanding of hominin dietary ecology, with implications for models of human evolution. $\delta^{13}C$ measurements of australopithecines show substantial dietary variation between, and in some cases, within species. The most startling comparison is between East and South African species of robust australopithecines. Both had exceptionally robust dental architecture and thick tooth enamel, and were formerly thought to have been specialized feeders who consumed hard foods such as seeds and nuts. More recently, studies of dental microwear have ruled out large quantities of hard foods such as grass seeds (Ungar, 2011). Isotope analyses show that the two ate very different diets: the East African *Paranthropus boisei* consumed mostly C_4-based foods (van der Merwe et al., 2008; Cerling et al., 2011), while the South African *Paranthropus robustus* ate a more mixed diet incorporating both C_3 and C_4 items. Quite what form the diet of *P. boisei* took is not yet clear; it may have focused on plants such as sedges. This work clearly shows that morphology alone does not provide an adequate basis for reconstructing dietary paleoecology.

The question of carnivory and/or herbivory in ancient diets recurs in different contexts, including the diets of extinct animals (Bocherens et al., 1994; Lee-Thorp et al., 2000) and Neanderthals. Neanderthal bones from central and eastern Europe have been shown to have very positive $\delta^{15}N$ (Bocherens, 2011, and references therein). There is stepwise fractionation of nitrogen isotopes with increasing trophic level, as mentioned above, so these individuals certainly ate large quantities of animal food. The amount of fractionation in a consumer compared with its food may, however, vary depending on diet (Sponheimer et al., 2003), and there have been changes in the carbon and nitrogen cycles since Neanderthal times (Bocherens et al., 2005; Stevens et al., 2008), making it difficult to ascertain the precise extent of carnivory.

A major application of stable carbon and nitrogen isotope analysis has been in distinguishing marine/terrestrial inputs into the diets of consumers. A few studies have focused on animals (Clementz et al., 2003; Chamberlain et al., 2005), but most have addressed the issue with archaeological humans. Dozens of papers have been published on this topic from many different parts of the world (e.g., Chisholm et al., 1982; Schoeninger et al., 1983; Sealy and van der Merwe, 1985; Yesner et al., 2003; Sealy, 2006; Quinn et al., 2008; Byers et al., 2011). One high-profile debate has been the extent to which the Mesolithic/Neolithic transition in Europe involved a shift away from marine foods toward a terrestrially oriented diet (Richards and Hedges, 1999; Richards et al., 2003; Milner et al., 2004, 2006; Richards and Schulting, 2006; Fischer et al., 2007).

Current research in paleodiet is extending the range of isotope methods. Isotopic analysis of individual chemical compounds enables much more specific tracing of foodstuffs, and greater resolution of complex mixtures of foods (Evershed et al., 2007). Less well-known isotopes ($^{2}H/^{1}H$, $^{44}Ca/^{40}Ca$) hold promise, as do studies of intra-individual variation to investigate seasonal differences in diet, migration, or age at weaning. Paleodietary studies can focus on single individuals or whole ecosystems, over time scales ranging from days or weeks to many millions of years. There will no doubt be an even greater range of applications in the future.

Bibliography

Ambrose, S. H., and Norr, L., 1993. Experimental evidence for the relationship of the carbon isotope ratio of whole diet and dietary protein to those of bone collagen and carbonate. In Lambert, J. B., and Grupe, G. (eds.), *Prehistoric Human Bone: Archaeology at the Molecular Level*. Berlin: Springer, pp. 1–37.

Ambrose, S. H., Butler, B. M., Hanson, D. B., Hunter-Anderson, R. L., and Krueger, H. W., 1997. Stable isotopic analysis of human diet in the Marianas Archipelago, western Pacific. *American Journal of Physical Anthropology*, **104**(3), 343–361.

Ayliffe, L. K., Chivas, A. R., and Leakey, M. G., 1994. The retention of primary oxygen isotope compositions of fossil elephant skeletal phosphate. *Geochimica et Cosmochimica Acta*, **58**(23), 5291–5298.

Balasse, M., 2002. Reconstructing dietary and environmental history from enamel isotopic analysis: time resolution of intra-tooth sequential sampling. *International Journal of Osteoarchaeology*, **12**, 155–165.

Bocherens, H., 2011. Diet and ecology of Neanderthals: implications from C and N isotopes. In Conard, N. J., and Richer, J. (eds.), *Neanderthal Lifeways, Subsistence and Technology: One Hundred Fifty Years of Neanderthal Study*. Dordrecht: Springer, pp. 73–85.

Bocherens, H., Fizet, M., and Mariotti, A., 1994. Diet, physiology and ecology of fossil mammals as inferred from stable carbon and nitrogen isotope biogeochemistry: implications for Pleistocene bears. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **107**(3–4), 213–225.

Bocherens, H., Drucker, D. G., Billiou, D., Patou-Mathis, M., and Vandermeersch, B., 2005. Isotopic evidence for diet and subsistence pattern of the Saint-Césaire I Neanderthal: review and use of a multi-source mixing model. *Journal of Human Evolution*, **49**(1), 71–87.

Brown, A. B., 1974. Bone strontium as a dietary indicator in human skeletal populations. *Contributions to Geology*, **13**(2), 47–48.

Buikstra, J. E., and Milner, G. R., 1991. Isotopic and archaeological interpretations of diet in the central Mississippi Valley. *Journal of Archaeological Science*, **18**(3), 319–329.

Burton, J. H., Price, T. D., and Middleton, W. D., 1999. Correlation of bone Ba/Ca and Sr/Ca due to biological purification of calcium. *Journal of Archaeological Science*, **26**(6), 609–616.

Byers, D. A., Yesner, D. R., Broughton, J. M., and Coltrain, J. B., 2011. Stable isotope chemistry, population histories and late prehistoric subsistence change in the Aleutian Islands. *Journal of Archaeological Science*, **38**(1), 183–196.

Cerling, T. E., and Harris, J. M., 1999. Carbon isotope fractionation between diet and bioapatite in ungulate mammals and implications for ecological and paleoecological studies. *Oecologia*, **120**(3), 347–363.

Cerling, T. E., Wang, Y., and Quade, J., 1993. Expansion of C4 ecosystems as an indicator of global ecological change in the late Miocene. *Nature*, **361**(6410), 344–345.

Cerling, T. E., Harris, J. M., MacFadden, B. J., Leakey, M. G., Quade, J., Eisenmann, V., and Ehleringer, J. R., 1997. Global vegetation change through the Miocene/Pliocene boundary. *Nature*, **389**(6547), 153–158.

Cerling, T. E., Mbua, E., Kirera, F. M., Manthi, F. K., Grine, F. E., Leakey, M. G., Sponheimer, M., and Uno, K. T., 2011. Diet of *Paranthropus boisei* in the early Pleistocene of East Africa. *Proceedings of the National Academy of Sciences*, **108**(23), 9337–9341.

Chamberlain, C. P., Waldbauer, J. R., Fox-Dobbs, K., Newsome, S. D., Koch, P. L., Smith, D. R., Church, M. E., Chamberlain, S. D., Sorenson, K. J., and Risebrough, R., 2005. Pleistocene to Recent dietary shifts in California condors: implications for conservation strategies. *Proceedings of the National Academy of Sciences*, **102**(46), 16707–16711.

Chisholm, B. S., Nelson, D. E., and Schwarcz, H. P., 1982. Stable-carbon isotope ratios as a measure of marine versus terrestrial protein in ancient diets. *Science*, **216**(4550), 1131–1132.

Clementz, M. T., Hoppe, K. A., and Koch, P. L., 2003. A paleoecological paradox: the habitat and dietary preferences of the extinct tethythere *Desmostylus*, inferred from stable isotope analysis. *Paleobiology*, **29**(4), 506–519.

Cox, G., Sealy, J., Schrire, C., and Morris, A., 2001. Stable carbon and nitrogen isotopic analyses of the underclass at the colonial Cape of Good Hope in the eighteenth and nineteenth centuries. *World Archaeology*, **33**(1), 73–97.

Edwards, E. J., Osborne, C. P., Strömberg, C. A. E., Smith, S. A., C_4 Grasses Consortium, Bond, W. J., Christin, P.-A., Cousins, A. B., Duvall, M. R., Fox, D. L., Freckleton, R. P., Ghannoum, O., Hartwell, J., Huang, Y., Janis, C. M., Keeley, J. E., Kellogg, E. A., Knapp, A. K., Leakey, A. D. B., Nelson, D. M., Saarela, J. M., Sage, R. F., Sala, O. E., Salamin, N., Still, C. J., and Tipple, B., 2010. The origins of C_4 grasslands: integrating evolutionary and ecosystem science. *Science*, **328**(5978), 587–591.

Evershed, R. P., Bull, I. D., Corr, L. T., Crossman, Z. M., van Dongen, B. E., Evans, C. J., Jim, S., Mottram, H. R., Mukherjee, A. J., and Pancost, R. D., 2007. Compound-specific stable isotope analysis in ecology and paleoecology. In Michener, R. H., and Lajtha, K. (eds.), *Stable Isotopes in Ecology and Environmental Science*, 2nd edn. Malden, MA: Blackwell, pp. 480–540.

Fischer, A., Olsen, J., Richards, M., Heinemeier, J., Sveinbjörnsdottír, Á. E., and Bennike, P., 2007. Coast-inland mobility and diet in the Danish Mesolithic and Neolithic: evidence from stable isotope values of humans and dogs. *Journal of Archaeological Science*, **34**(12), 2125–2150.

Friedli, H., Lötscher, H., Oeschger, H., Siegenthaler, U., and Stauffer, B., 1986. Ice core record of the $^{13}C/^{12}C$ ratio of atmospheric CO_2 in the past two centuries. *Nature*, **324**(6094), 237–238.

Fry, B., 2006. *Stable Isotope Ecology*. New York: Springer.

Hedges, R. E. M., and Reynard, L. M., 2007. Nitrogen isotopes and the trophic level of humans in archaeology. *Journal of Archaeological Science*, **34**(8), 1240–1251.

Hoefs, J., 2009. *Stable Isotope Geochemistry*, 6th edn. Berlin: Springer.

Howland, M. R., Corr, L. T., Young, S. M. M., Jones, V., Jim, S., van der Merwe, N. J., Mitchell, A. D., and Evershed, R. P., 2003. Expression of the dietary isotope signal in the compound-specific $\delta^{13}C$ values of pig bone lipids and amino acids. *International Journal of Osteoarchaeology*, **13**(1–2), 54–65.

Jim, S., Ambrose, S. H., and Evershed, R. P., 2004. Stable carbon isotopic evidence for differences in the dietary origin of bone cholesterol, collagen and apatite: implications for their use in palaeodietary reconstruction. *Geochimica et Cosmochimica Acta*, **68**(1), 61–72.

Koch, P. L., 2007. Isotopic study of the biology of modern and fossil vertebrates. In Michener, R. H., and Lajtha, K. (eds.), *Stable Isotopes in Ecology and Environmental Science*, 2nd edn. Malden, MA: Blackwell, pp. 99–154.

Koch, P. L., Tuross, N., and Fogel, M. L., 1997. The effects of sample treatment and diagenesis on the isotopic integrity of carbonate in biogenic hydroxylapatite. *Journal of Archaeological Science*, **24**(5), 417–429.

Lee-Thorp, J. A., 2002. Two decades of progress towards understanding fossilization processes and isotopic signals in calcified tissue minerals. *Archaeometry*, **44**(3), 435–446.

Lee-Thorp, J. A., 2008. On isotopes and old bones. *Archaeometry*, **50**(6), 925–950.

Lee-Thorp, J., and Sponheimer, M., 2006. Contributions of biogeochemistry to understanding hominin dietary ecology. Yearbook of Physical Anthropology 49. *American Journal of Physical Anthropology*, **131**(Suppl 43), 131–148.

Lee-Thorp, J. A., Thackeray, J. F., and van der Merwe, N., 2000. The hunters and the hunted revisited. *Journal of Human Evolution*, **39**(6), 565–576.

Leuenberger, M., Siegenthaler, U., and Langway, C., 1992. Carbon isotope composition of atmospheric CO_2 during the last ice age from an Antarctic ice core. *Nature*, **357**(6378), 488–490.

Loftus, E., and Sealy, J., 2012. Interpreting stable carbon isotopes in human tooth enamel: an examination of tissue spacings from South Africa. *American Journal of Physical Anthropology*, **147**(3), 499–507.

Meier-Augenstein, W., and Fraser, I., 2008. Forensic isotope analysis leads to identification of a mutilated murder victim. *Science and Justice*, **48**(3), 153–159.

Michener, R. H., and Lajtha, K. (eds.), 2007. *Stable Isotopes in Ecology and Environmental Science*, 2nd edn. Malden, MA: Blackwell.

Miller, G. H., Fogel, M. L., Magee, J. W., Gagan, M. K., Clarke, S. J., and Johnson, B. J., 2005. Ecosystem collapse in Pleistocene Australia and a human role in megafaunal extinction. *Science*, **309**(5732), 287–290.

Milner, N., Craig, O. E., Bailey, G. N., Pederson, K., and Andersen, S. H., 2004. Something fishy in the Neolithic? A re-evaluation of stable isotope analysis of Mesolithic and Neolithic coastal populations. *Antiquity*, **78**(299), 9–22.

Milner, N., Craig, O. E., Bailey, G. N., and Andersen, S. H., 2006. A response to Richards and Schulting. *Antiquity*, **80**(308), 456–458.

Müller, W., Fricke, H., Halliday, A. N., McCulloch, M. T., and Wartho, J.-A., 2003. Origin and migration of the Alpine Iceman. *Science*, **302**(5646), 862–866.

O'Leary, M. H., 1988. Carbon isotopes in photosynthesis. *BioScience*, **38**(5), 328–336.

Passey, B. H., Robinson, T. F., Ayliffe, L. K., Cerling, T. E., Sponheimer, M., Dearing, M. D., Roeder, B. L., and Ehleringer, J. R., 2005. Carbon isotope fractionation between diet, breath CO_2, and bioapatite in different mammals. *Journal of Archaeological Science*, **32**(10), 1459–1470.

Phillips, D. L., 2001. Mixing models in analyses of diet using multiple stable isotopes: a critique. *Oecologia*, **127**(2), 166–170.

Phillips, D. L., and Koch, P. L., 2002. Incorporating concentration dependence in stable isotope mixing models. *Oecologia*, **130**(1), 114–125.

Phillips, D. L., Newsome, S. D., and Gregg, J. W., 2005. Combining sources in stable isotope mixing models: alternative methods. *Oecologia*, **144**(4), 520–527.

Price, T. D., Bentley, R. A., Lüning, J., Gronenborn, D., and Wahl, J., 2001. Prehistoric human migration in the Linearbandkeramik of Central Europe. *Antiquity*, **75**(289), 593–603.

Price, T. D., Tiesler, V., and Burton, J. H., 2006. Early African diaspora in colonial Campeche, Mexico: strontium isotopic evidence. *American Journal of Physical Anthropology*, **130**(4), 485–490.

Quinn, R. L., Tucker, B. D., and Krigbaum, J., 2008. Diet and mobility in Middle Archaic Florida: stable isotopic and faunal evidence from the Harris Creek archaeological site (8Vo24), Tick Island. *Journal of Archaeological Science*, **35**(8), 2346–2356.

Richards, M. P., and Hedges, R. E. M., 1999. A Neolithic revolution? New evidence of diet in the British Neolithic. *Antiquity*, **73**(282), 891–897.

Richards, M. P., and Schulting, R. J., 2006. Touch not the fish: the Mesolithic-Neolithic change of diet and significance. *Antiquity*, **80**(308), 444–456.

Richards, M. P., Price, T. D., and Koch, E., 2003. Mesolithic and Neolithic subsistence in Denmark: new stable isotope data. *Current Anthropology*, **44**(2), 288–295.

Richards, M. P., Greer, S., Corr, L. T., Beattie, O., Mackie, A., Evershed, R. P., von Finster, A., and Southon, J., 2007. Radiocarbon dating and dietary stable isotope analysis of Kwaday Dän Ts'inchí. *American Antiquity*, **72**(4), 719–733.

Schoeninger, M. J., 1979. Diet and status at Chalcatzingo: some empirical and technical aspects of strontium analysis. *American Journal of Physical Anthropology*, **51**(3), 295–310.

Schoeninger, M. J., DeNiro, M. J., and Tauber, H., 1983. Stable nitrogen isotope ratios of bone collagen reflect marine and terrestrial components of prehistoric human diet. *Science*, **220**(4604), 1381–1383.

Sealy, J., 2006. Diet, mobility and settlement pattern among Holocene hunter-gatherers in southernmost Africa. *Current Anthropology*, **47**(4), 569–595.

Sealy, J. C., and van der Merwe, N. J., 1985. Isotope assessment of Holocene human diets in the southwestern Cape, South Africa. *Nature*, **315**(6105), 138–140.

Sealy, J., Armstrong, R., and Schrire, C., 1995. Beyond lifetime averages: tracing life histories through isotopic analysis of different calcified tissues from archaeological human skeletons. *Antiquity*, **69**(263), 290–300.

Sharp, Z., 2007. *Principles of Stable Isotope Geochemistry*. Upper Saddle River, NJ: Pearson/Prentice Hall.

Sillen, A., and Kavanagh, M., 1982. Strontium and paleodietary research: a review. Yearbook of Physical Anthropology. *American Journal of Physical Anthropology*, **25**(Suppl 3), 67–90.

Sponheimer, M., Robinson, T., Ayliffe, L., Roeder, B., Hammer, J., Passey, B., West, A., Cerling, T., Dearing, D., and Ehleringer, J., 2003. Nitrogen isotopes in mammalian herbivores: hair $\delta^{15}N$ values from a controlled feeding study. *International Journal of Osteoarchaeology*, **13**(1–2), 80–87.

Sponheimer, M., Passey, B. H., de Ruiter, D. J., Guatelli-Steinberg, D., Cerling, T. E., and Lee-Thorp, J. A., 2006. Isotopic evidence for dietary variability in the early hominin *Paranthropus robustus. Science*, **314**(5801), 980–982.

Stevens, R. E., Jacobi, R., Street, M., Germonpré, M., Conard, N. J., Münzel, S. C., and Hedges, R. E. M., 2008. Nitrogen isotope analyses of reindeer (*Rangifer tarandus*), 45,000 BP to 9,000 BP: palaeoenvironmental reconstructions. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **262** (1–2), 32–45.

Stott, A. W., Evershed, R. P., Jim, S., Jones, V., Rogers, J. M., Tuross, N., and Ambrose, S., 1999. Cholesterol as a new source of palaeodietary information: experimental approaches and archaeological applications. *Journal of Archaeological Science*, **26**(6), 705–716.

Tieszen, L. L., and Fagre, T., 1993. Effects of diet quality and composition on the isotopic composition of respiratory CO_2, bone collagen, bioapatite, and soft tissues. In Lambert, J. B., and Grupe, G. (eds.), *Prehistoric Human Bone: Archaeology at the Molecular Level*. Berlin: Springer, pp. 121–155.

Trudinger, C. M., Enting, I. G., Rayner, P. J., and Francey, R. J., 2002. Kalman filter analysis of ice core data 2. Double deconvolution of CO_2 and $\delta^{13}C$ measurements. *Journal of Geophysical Research: Atmospheres (1984–2012)*, **107**(D20), ACH 5-1–ACH 5-24.

Ungar, P., 2011. Dental evidence for the diets of Plio-Pleistocene hominins. Yearbook of Physical Anthropology. *American Journal of Physical Anthropology*, **146**(Suppl 53), 47–62.

Ungar, P. S., and Sponheimer, M., 2011. The diets of early hominins. *Science*, **334**(6053), 190–193.

Van der Merwe, N. J., and Vogel, J. C., 1978. ^{13}C content of human collagen as a measure of prehistoric diet in woodland North America. *Nature*, **276**(5690), 815–816.
Van der Merwe, N. J., Masao, F. T., and Bamford, M. K., 2008. Isotopic evidence for contrasting diets of early hominins *Homo habilis* and *Australopithecus boisei* of Tanzania. *South African Journal of Science*, **104**(3–4), 153–155.
Van Klinken, G. J., 1999. Bone collagen quality indicators for palaeodietary and radiocarbon measurements. *Journal of Archaeological Science*, **26**(6), 687–695.
Vogel, J. C., and van der Merwe, N. J., 1977. Isotopic evidence for early maize cultivation in New York State. *American Antiquity*, **42**(2), 238–242.
Wang, Y., and Cerling, T. E., 1994. A model of fossil tooth and bone diagenesis: implications for paleodiet reconstruction from stable isotopes. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **107**(3–4), 281–289.
Wang, Y., Cerling, T. E., and MacFadden, B. J., 1994. Fossil horses and carbon isotopes: new evidence for Cenozoic dietary, habitat, and ecosystem changes in North America. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **107**(3–4), 269–279.
Warinner, C., and Tuross, N., 2009. Alkaline cooking and stable isotope tissue-diet spacing in swine: archaeological implications. *Journal of Archaeological Science*, **36**(8), 1690–1697.
Wright, L. E., and Schwarcz, H. P., 1998. Stable carbon and oxygen isotopes in human tooth enamel: identifying breastfeeding and weaning in prehistory. *American Journal of Physical Anthropology*, **106**(1), 1–18; erratum **106**(3), 411.
Yesner, D. R., Torres, M. J. F., Guichon, R. A., and Borrero, L. A., 2003. Stable isotope analysis of human bone and ethnohistoric subsistence patterns in Tierra del Fuego. *Journal of Anthropological Archaeology*, **22**(3), 279–291.
Zachos, J., Pagani, M., Sloan, L., Thomas, E., and Billups, K., 2001. Trends, rhythms, and aberrations in global climate 65 Ma to present. *Science*, **292**(5517), 686–693.

Cross-references

Oxygen Isotopes
Stable Carbon Isotopes in Soils

PALEOENVIRONMENTAL RECONSTRUCTION

Rolfe D. Mandel[1] and Vance T. Holliday[2]
[1]Department of Anthropology, University of Kansas, Lawrence, KS, USA
[2]Anthropology and Departments Geosciences, University of Arizona, Tucson, AZ, USA

Introduction

A major component of geoarchaeology is the reconstruction of paleoenvironments at archaeological sites or within a region. Paleoenvironmental information can be essential for understanding the environment before, during, and after site occupation, and it may provide insights into environmental changes that influenced technology, social structure, human subsistence, and settlement strategies. According to Rapp and Hill (2006, 187), "The impact of the earth's environmental and climatic patterns on human physical and behavioral development, and the effect of prehistoric human behavior on changing environmental landscapes, can be pursued by means of a geoarchaeological approach as part of a broader geoecological perspective."

Karl Butzer was the first geoarchaeologist to place a strong emphasis on paleoenvironmental reconstruction, a theme echoed in his 1964 and 1971 books, *Environment and Archaeology* (Butzer, 1964; Butzer, 1971). Over the past 50 years, geoarchaeologists have become more engaged in paleoenvironmental reconstruction, and it is now quite common for archaeologists to engage in paleoecological research with the collaboration of geologists, geographers, soil scientists, paleobotanists, and paleontologists.

The significance of environmental change on the evolution of humans has long been acknowledged, and according to Blockley et al. (2012), those changes "underpin many of the proposed mechanisms behind models of human evolution, including population movement, isolation, specific adaptations and speciation." For example, environmental change has been identified as one of the key factors behind the migration of the first hominins out of Africa. At Dmanisi in the Republic of Georgia, where the earliest evidence of *Homo erectus* outside Africa has been found, paleoenvironmental evidence suggests the existence of sparse vegetation and a semiarid landscape at the time of occupation (ca. 1.8 Ma BP) (Gabunia et al., 2000). This may have been an ideal environment for a species considered to be an arid-adapted hominin. Similarly, in Indonesia, glacial climatic episodes after ca. 1.8 Ma BP may have promoted the development of open woodland and grassland mosaic environments for Javan *H. erectus* to exploit (Bettis et al., 2009).

In the context of paleoenvironmental reconstruction, a distinction must be drawn between "environment" (a more general term) and "climate" (a more specific term). *Environment* "encompasses all the physical and biological elements and relationships that impinge upon a living being" (Dincauze, 2000, 3), including the climate, plants (flora), animals (fauna), and landscape setting. *Climate*, in contrast, refers to the regional, long-term characteristics of weather patterns such as average precipitation, average temperatures, and seasonal fluctuations, i.e., "the atmospheric conditions typical of the location" (Aguado and Burt, 1999, 381). By looking at proxy indicators of climate, the intent is usually to gain access to relatively specific kinds of information about temperature or precipitation. The reconstruction of environments, however, can be much more general, but also very localized, such as the reconstruction of poorly drained, bog-like conditions, which can be fairly restricted in area.

The reconstruction of paleoenvironments typically involves the analysis of abiotic and/or biotic evidence. Abiotic evidence includes geomorphic, sedimentologic, and stratigraphic attributes, and biotic evidence consists of plant and animal remains as well as evidence of other living things. In addition, there are geochemical indicators of paleoenvironments, primarily the stable isotope composition of sediments, soil organic matter, soil nodules, and carbonates. With the exception of geochemical indicators, which are addressed elsewhere in this encyclopedia, the *primary* sources of paleoenvironmental information used in geoarchaeolgical studies are briefly described below. Also presented are examples of the application of paleoenvironmental data in geoarchaeological investigations.

Abiotic evidence

Geomorphic, sedimentologic, and stratigraphic indicators

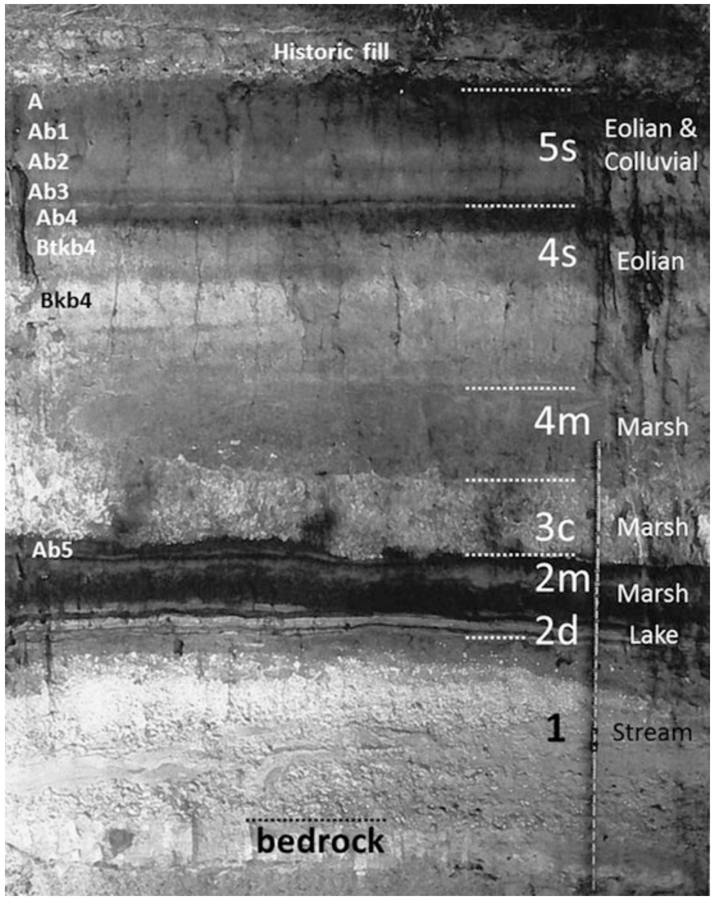
Descriptions and analysis of landforms, sediments, and stratigraphic sequences at and near archaeological sites provide a way to identify depositional processes and past environments (also see the entries on "Sedimentology" and "Stratigraphy" in this volume). As discussed in the entry on "Site Formation Processes" (also in this volume), various depositional processes and depositional settings produce characteristic sedimentologic and stratigraphic assemblages. Paleoenvironmental interpretations are based on comparisons of the attributes of prior landforms together with their associated sediments and stratigraphic sequences with the characteristics of modern landscapes and depositional environments. In short, understanding the processes that form landscapes and deliver sediments at and near archaeological sites is crucial in any attempt to reconstruct environments that existed before, during, and after a site or region was occupied.

Geomorphology was used as an indicator of paleoenvironments in a geoarchaeological investigation near Kharga in the Western Desert of Egypt (Mandel and Simmons, 2001). That study recorded many small playas, or pans, on the Libyan Plateau, overlooking the Kharga Depression. Dense concentrations of artifacts were recorded on the edges of the pans (Figure 1), indicating that these geomorphic features were focal points for human occupation, presumably when they held water. For the area that was surveyed, Middle Paleolithic, Terminal Paleolithic, and Neolithic occupations are strongly tied to pans. Unlike the spring-fed lakes in the Nubian Desert, the pans on the Plateau received all of their water from local rainfall; they were never influenced by precipitation farther south that recharged the regional aquifer, which in turn supplied water to spring-fed lakes in the Kharga Depression. Hence, the relationship between the temporally diagnostic artifact assemblages and pans supports the hypothesis that monsoonal summer rains of central Africa periodically penetrated at least as far north as Kharga at various times during late-Quaternary wet phases (pluvials) (Mandel and Simmons, 2001).

Geoarchaeological investigations in the dry valleys, or draws, of the Southern High Plains in northwestern Texas and eastern New Mexico demonstrated how sedimentology could be used to infer late-Quaternary environmental change (Holliday, 1985; Holliday, 1995; Holliday, 1997) (see the entry on "Great Plains Geoarchaeology"). Much of the paleoenvironmental information was gleaned from stratigraphic sequences at two sites: Lubbock Lake in Yellowhouse Draw (Figures 2 and 3) and Clovis in Blackwater Draw (Figure 4). From the terminal Pleistocene to the early Holocene, there was a hydrologic shift from flowing water (based on the accumulation of alluvium and spring sands) to standing water (indicated by the accumulation of diatomaceous and palustrine muds), then to the almost complete disappearance of surface water and the deposition of eolian sands. These environmental changes resulted from a decrease in effective regional precipitation from the late Pleistocene to the middle Holocene (Holliday, 1995).

Paleoenvironmental Reconstruction, Figure 1 View of fire-cracked rocks and Terminal Paleolithic artifacts along a 75-m-long shoreline of a shallow basin, or pan, on a portion of the Libyan Plateau in the hyper-arid Western Desert of Egypt. The pan, which apparently held water during the terminal Pleistocene, is a good example of geomorphic evidence of a former wetter climate in the region (Photograph from Mandel and Simmons (2001: Figure 5)).

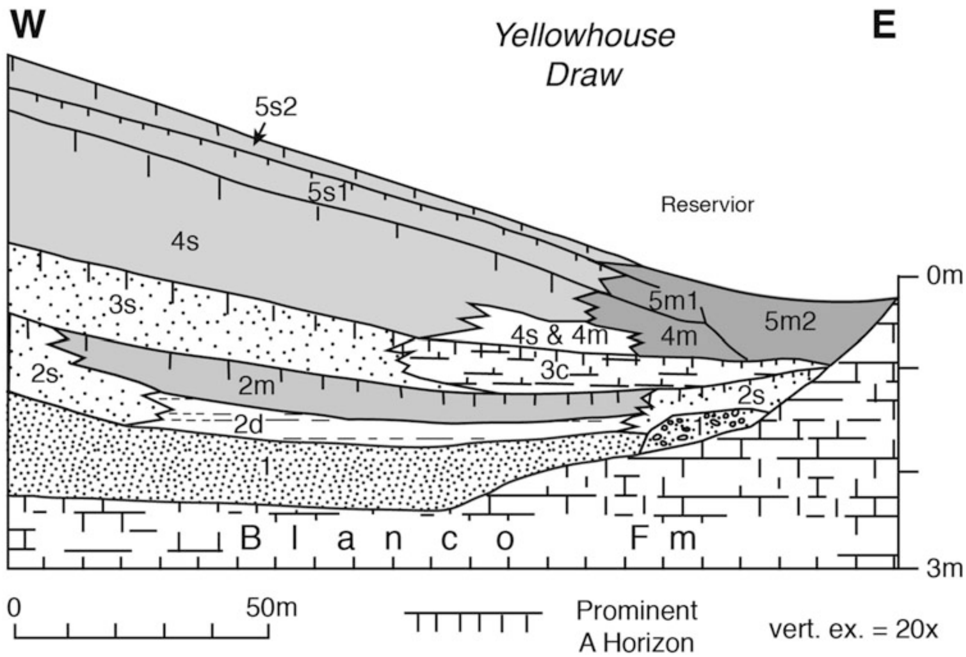
At the Winger site on the High Plains of southwestern Kansas, local and regional environmental changes spanning most of the Holocene were inferred from the



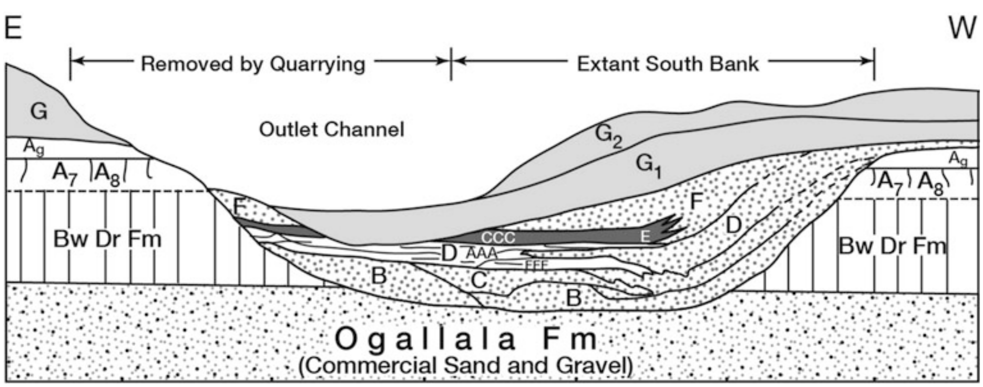
Paleoenvironmental Reconstruction, Figure 2 Photograph of a stratigraphic section at the Lubbock Lake archaeological site in northwest Texas. The section was exposed along the valley axis of Yellowhouse Draw (see also Figure 3). The lithostratigraphy (1–5; m = marsh muds, d = diatomite, and s = sandy eolian facies) and depositional environments are indicated to the *right*. A simplified soil stratigraphy is shown on the *left*. The rod is 3 m long (Photo from the Museum of Texas Tech University and labeled by V. T. Holliday).

geomorphology, stratigraphy, and sedimentology of the site. A deeply buried bone bed representing a Late Paleoindian bison kill at Winger occurs in a former playa basin (Mandel and Hofman, 2003). The bone bed dates to ca. 9100 ^{14}C yr BP and is in a buried soil developed in clayey, organic-rich basin fill overlain by early Holocene alluvium (arroyo fill) (Figure 5). Recent alluvium overlies a truncated soil developed in the early Holocene alluvium, and modern deposits of eolian sand 2 m to 35 cm thick mantle the site area. Based on the stratigraphic context of the bone bed, the playa fill was aggrading at the time of the bison kill. The bison bones were quickly buried in lacustrine sediments, followed by an episode of landscape stability and concomitant soil formation in the playa. There was a major change in the sedimentary environment soon after ca. 9100 ^{14}C yr BP, with Bear Creek breaching the margin of the playa basin and depositing alluvium on top of the lacustrine sediments. Alluviation during the early Holocene was followed by a period of soil formation around 8500 ^{14}C yr BP, then net erosion during the middle Holocene. The episode of mid-Holocene erosion in western Kansas is attributed to aridity and reduced vegetative cover (Mandel, 2006). A brief episode of late-Holocene alluviation at Winger was followed by accumulation of eolian sands during the Historic period as dunes buried the site.

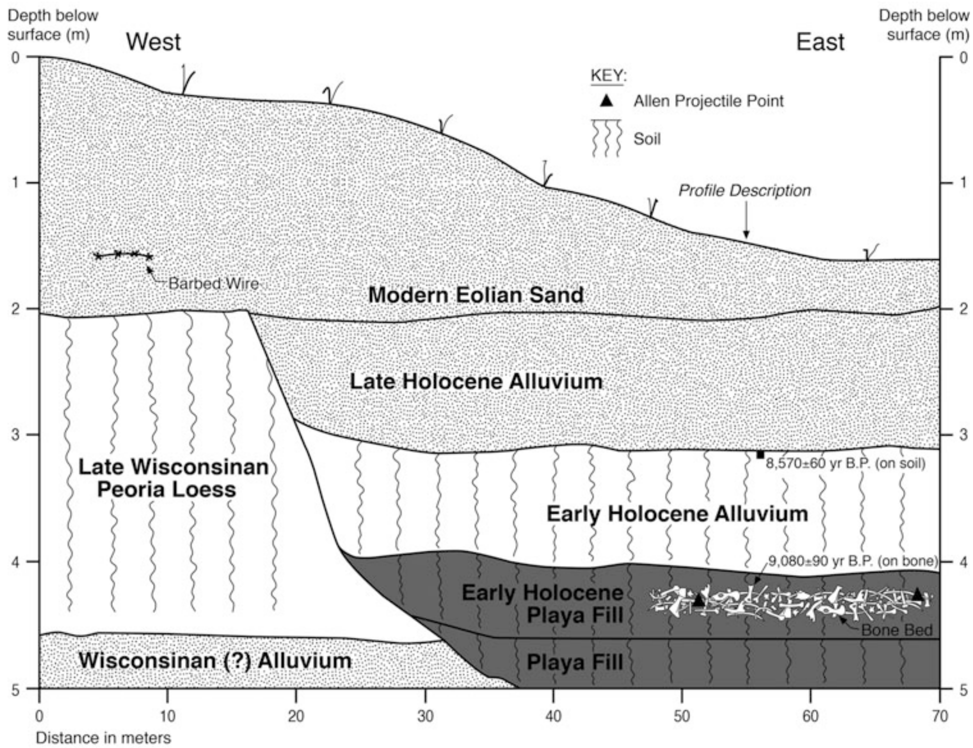
Detailed analyses of sediments and microstratigraphy were used to reconstruct terminal Pleistocene and early Holocene paleoenvironments at the Wasden site in Idaho (Moody and Dort, 1990). Those analyses revealed that the sediments contained within the Coyote Cave depression, a part of the Wasden site, were derived from various materials on the Snake River Plain and deposited by alluvial and eolian processes. Moody and Dort (1990, 367) noted that the physical properties of the sediment, especially grain-size distribution, provided "information about environmental conditions both at the Wasden site itself and in the surrounding area during and between times of



Paleoenvironmental Reconstruction, Figure 3 Stratigraphic cross-section across Yellowhouse Draw at the Lubbock Lake site (see also Figure 2). The bedrock is the Blanco Formation (Pliocene) and was incised in the late Pleistocene. Stratum 1 is gravel, sand, and clay alluvium deposited ≥11,000 ^{14}C yr BP. It contains Clovis-age fauna and archaeological remains. Stratum 2 includes diatomite beds (2d) and Folsom occupation debris deposited in a lake and lake margin settings ~11,000 to ~10,000 ^{14}C yr BP. Stratum 2d evolved into marsh muds (2 m) that persisted from ~10,000 ^{14}C yr BP until ~6500 ^{14}C yr BP, with stability and soil formation. Both 2d and 2 s strata have valley margin sandy eolian facies (2 s). Late Paleoindian features are common in stratum 2 m, but Early Archaic remains are rare. From ~6500 to ~5500 ^{14}C yr BP, marl (Stratum 3c) accumulated in a hardwater marsh along the valley axis. Brief incision and localized deposition of marsh muds (stratum 4 m) were followed by widespread deposition of sandy eolian sediments (stratum 4 s) from ~5500 to ~4500 ^{14}C yr BP. Middle Archaic occupations are rare but present in stratum 4 s. Stability with concomitant pedogenesis ensued for most of the rest of the Holocene. Late Archaic and late prehistoric archaeology is locally common in the soil. Starting ~1000 ^{14}C yr BP, episodic deposition of eolian and colluvial sediments (stratum 5 s with soils) locally buried stratum 4. The stratum 5 sequence includes Late Prehistoric, Proto-historic, and Historic Native American features and Historic European occupations (Diagram from Holliday (1995: Figure 28B)).



Paleoenvironmental Reconstruction, Figure 4 Generalized east–west geologic cross-section of the south end of the Clovis site paleobasin. The basin fill is inset into the Ogallala Formation and Blackwater Draw Formation (Bw Dr Fm and A_7, A_8 and A_9). The oldest basin fill is spring-laid sand divided into Unit B (13,000–11,500 ^{14}C yr BP) and Unit C (11,500–11,000 ^{14}C yr BP) and separated by an unconformity. The Unit B and C sands have yielded Clovis artifacts. Units D and E consist of diatomaceous earth (pond deposit) and an organic-rich sandy mud (marsh deposit), respectively. Most of the Paleoindian features were found in units D and E. Eolian sands comprise units F and G. Also shown are the stratigraphic relationships of the Paleoindian archaeological components (FFF = Folsom, AAA = Agate Basin, and CCC = Cody/Firstview) to the basin fill (Diagram from Holliday (1997: Figure 3.10) as modified from Haynes (1995: Figure 7)).



Paleoenvironmental Reconstruction, Figure 5 Stratigraphic cross-section of the exposure at the Winger site, a Late Paleoindian bison kill in southwestern Kansas. From the early Holocene to Historic period, there was a hydrologic shift from standing water (accumulation of lacustrine sediments) to flowing water (accumulation of alluvium), then accumulation of eolian sands. Erosion during the middle Holocene and the development of sand dunes during the Historic period are attributed to a decrease in effective regional precipitation (Diagram from Mandel and Hofman (2003: Figure 6)).

occupation of the cave." For example, alternating beds of very fine sandy loam and silt loam underlying the ramp in front of Coyote Cave were attributed to episodes of local dune activity and regional loess deposition, respectively, and the loess was considered the product of a relatively dry eolian climatic regime.

Soils

Soils are intimately related to the environment because soil development is directly linked to local environmental conditions. The nature of past environments has long been a fundamental question in archaeology, and therefore many attempts have been made to use soils from archaeological contexts to provide paleoenvironmental reconstructions. Such attempts have met with mixed success, however, because the relationship between soil genesis and environmental conditions is very complex. Moreover, using a specific soil or soil characteristic to reconstruct paleoenvironmental specifics, such as past climate conditions, can be difficult.

As previously noted, it is important to distinguish between "environment" and "climate" for the purposes of paleoenvironmental reconstruction. Soils are better suited for environmental reconstructions, though the discussion below will explain that, under some circumstances, a degree of climatic or even vegetation specificity can be involved.

Climate influences pedogenesis most directly through precipitation and temperature, and indirectly through flora and fauna. The most direct impacts produced by biota probably come from (1) the addition of a wide range of chemical compounds, (2) bioturbation, and (3) rooting. Using soils to reconstruct past climatic and biotic conditions, however, has proven to be very difficult for a number of reasons. Plant and animal communities are closely linked to one another and to climate, and consequently, it is difficult to sort out the varied influences in the factorial approach (Jenny, 1941, 197–199; Birkeland, 1984, 165, 260; Birkeland, 1999, 268). Further, soils are not sufficiently sensitive in responding to discrete climate changes that may be culturally significant. Such changes can be more readily detected using plant or animal remains, particularly in a high-resolution, microstratigraphic context. However, as is the case with many environmental proxies, the microclimate and local vegetation can influence local soil forming processes in a dominant way, thus obscuring the regional climatic and vegetation

Paleoenvironmental Reconstruction, Table 1 Paleoenvironmental Indicators from soils (From Holliday, 2004: chapter 8).

Soil characteristic		Environmental characteristic
Color	Dark color[a]	High soil organic-matter production under relatively wet conditions; can include the surface horizon of grassland and forest soils and also thicker peats and bog-related soils.
	Red color	Red or reddish-brown colors generally indicate well-drained conditions; a deep, reddish-brown, "coffee" color can indicate iron translocation under intense "podzolic" leaching conditions (see below).
	Gray, greenish-gray, bluish-gray, or gley colors[b]	Reducing conditions promoting either reduction (usually high water table) and reprecipitation of Fe or Mn, or leaching of Fe or Mn out of the soil.
Zones of $CaCO_3$ accumulation	Bk, Bkm, and K horizon (calcic or petrocalcic horizon)	These zones form when calcium and bicarbonate ions are available in the soil solution and evaporation exceeds precipitation; they are ubiquitous pedogenic characteristics in arid and semi-arid environments. A wide variety of factors, in addition to precipitation and evapotranspiration, have a significant impact on the morphology and depth of these horizons.
E horizon and podzolic characteristics	E horizon	Formation of an E horizon represents leaching (eluviation) of clay, iron, aluminum, organic matter, or a combination of these constituents, leaving a lighter colored zone with a concentration of sand-sized or silt-sized quartz just below the A horizon and above the B; usually takes place under humid, forested settings.
	Podzolization	A particularly intense form of leaching and translocation of iron, aluminum, or organic matter out of the E horizon and precipitation within the B horizon. The result is a strongly expressed E or albic horizon and Bh, Bs, or Bhs spodic horizon. Key environmental ingredients in podzolization are coarse parent material (enhancing rapid, deep leaching), abundant water, and vegetation that produces a thick, acidic litter, such as coniferous forests, heather, or lichen-heath in the tundra. An E horizon, therefore, is broadly indicative of the pedogenic environment – in particular, humid, forested conditions.
Cryogenic characteristics[c]	Solifluction	Contorted beds and soils.
	Gelifluction	A type of solifluction; slow down-slope movement of water-saturated soil above permafrost.
	Micromorphology	Disruption of clay films lining voids, formed in earlier temperate periods and incorporated into the soil matrix (as "papules"); silty cappings on sand particles, platy structure; rounded granules of illuvial silt; accumulation of soil or sand in fissures or coarse pores, and large rounded pores or vesicles produced by air bubbles during thawing of ground-ice.

[a]Low chromas and values in the Munsell soil color system.
[b]Chroma typically <2.
[c]Formed by *cryoturbation*, which refers to soil mixing due to freezing and thawing of the ground.

conditions that may be of interest. In addition, climate changes in the Holocene, the time period with which most North American archaeologists work, were often of insufficient magnitude to be detectable in the pedological record.

The properties of soils that seem to be the best indicators of the climatic conditions during which soil formation occurred include organic matter content, the depth of leaching (which determines the presence or absence of $CaCO_3$ and more soluble salts), depth to the top of the zone of accumulation of the carbonate or salts, and overall profile morphology (Table 1).

There is only a limited amount of information that helps to identify the pedological features most closely related to past plant and animal communities. Further, as noted above, the distribution of plants and animals is so intimately linked to climate that sorting out the effects of each is often difficult. The soil characteristics that seem to be most directly indicative of vegetation and that also persist in buried soils over long intervals are the E horizon and related podzolic characteristics, and some overall profile morphologies.

A significant environmental characteristic of soils is that they are largely the products of immediate, localized conditions. The physical, chemical, and biological characteristics of a soil profile were determined by the parent material at that site, by the flora and fauna living at that site, and by the meteorological conditions (such as precipitation and temperature) that operated on the site over time. This is in contrast to other proxy environmental indicators (e.g., sediment characteristics, pollen) that are affected by both regional and local conditions.

In using soils to reconstruct environmental conditions, therefore, the key is selecting those pedogenic characteristics that are indicative of relatively specific conditions such as drainage, topographic setting, rainfall, or plant communities. The best results in using soils as paleoenvironmental indicators seem to be obtained for local environmental reconstructions. Soils are particularly useful in assessing local drainage conditions and paleotopographic settings because pedogenesis is sensitive to both surface and subsurface water movement and because the topographic setting affects water movement.

The localized nature of pedogenesis also raises a cautionary issue. The reconstruction of regional environments using soils should not be based on one or a few soils from an archaeological site because local pedogenic conditions may not necessarily reflect regional environmental conditions. The reasons why an archaeological site is located where it is may be due to unusual characteristics, such as access to water or other resources – characteristics that may have a profound impact on local pedogenesis but may not be expressed in the regional soils of the same age and stratigraphic position. Springs, for example, are key locations of hominin and animal activity and as such have been the focus of archaeological research. However, spring localities are microenvironments and, therefore, are not necessarily representative of regional environmental conditions. On the contrary, the very conditions that make springs attractive to people (water along with availability of floral and faunal resources) may be because of the absence of such conditions elsewhere in the region (e.g., Haynes and Agogino, 1966; Haynes, 1975; Holliday, 1985; Haynes, 1995; Holliday, 1995; Ashley, 2001; Holliday et al., 2007; Ashley et al., 2009; Haynes and Warnica, 2012).

Equifinality is also an issue in the paleoenvironmental interpretation of soils. In particular, long periods of soil formation apparently can produce some pedological characteristics similar to those produced under particular climatic conditions. As a corollary to equifinality, relatively few specific soil features or types of surface or buried soils are related to unique or easily circumscribed environments of formation. For example, argillic horizons occur in modern surface soils in a wide variety of environments throughout North America.

The polygenetic nature of soils can also confound their paleoenvironmental signal: the very characteristics that make soils useful as indicators of the passage of time compromise their utility as paleoenvironmental proxies. As soils form through time they may be subjected to a succession of environments. The longer the duration of pedogenesis, the more changes a soil will likely experience, i.e., the more polygenetic it will be. At best, therefore, soils represent some sort of "averaging" or mixing of whatever morphological and chemical characteristics may be linked to the environment. Broadly speaking, soils that formed over relatively short periods and did not experience many environmental changes are more useful for reconstructing the environmental conditions at the time of pedogenesis than are soils that formed over a longer interval and were subjected to a variety of environments (or at least much more effort is required to reconstruct the environmental history of polygenetic soils). The problem with pedological features that develop relatively quickly, however, is that they tend not to persist in buried soils (Yaalon, 1971).

Finally, a stratigraphic sequence with a buried soil, though suggestive of changes in landscape stability, is not necessarily indicative of environmental changes. Certainly this is the case with multiple weakly expressed A-C soils buried in floodplain deposits. The cycles of sedimentation and stability are simply part of the natural evolution of a floodplain, relating to variability in precipitation and runoff from year to year (Ferring, 1986; Brown, 1997, 96–103; Ferring, 2001). Soils can also be buried due to human activities such as construction (e.g., Leighton, 1933; Bettis, 1988; Sandor, 1992; Cremeens, 1995; Alexandrovskiy, 2000) or human-induced soil erosion (e.g., Overstreet and Grolier, 1988; de Maigret et al., 1989; Fedele, 1990; Wilkinson, 1997).

There have been many studies in which soils were used for paleoenvironmental reconstruction at archaeological sites. For example, Reider (1980, 1982a, 1982b, 1990) noted that soils at terminal Pleistocene archaeological sites in Wyoming and eastern Colorado are mostly Aquolls and Argialbolls with properties indicative of a generally cool, humid environment. By contrast, calcareous or alkaline soils (Calciustolls and Natrargids) at sites dating to the middle Holocene thermal maximum, the Altithermal (ca. 8000–4000 BP), were interpreted as evidence of significant climatic drying. Reider (1990) suggested that weak development in post-Altithermal soils probably reflects general landscape instability associated with fluctuating Neoglacial climates in the region.

Soils also have provided clues to the paleoenvironmental context of hominin sites in Olduvai Gorge, Tanzania. Ashley and Driese (2000) identified a buried paleocatena in proximity to wetlands and dated it to ~1.75 Ma. The buried soils were then used to reconstruct the evolution of the local paleohydrology. The paleocatena was identified within a "cumulative red paleosol" formed in volcaniclastic parent material, and it was differentiated into an upslope and a downslope facies (over a distance of about 1 km). Compared to the downslope facies, the upslope facies was characterized by less evidence for plant rooting, greater clay translocation, and greater zeolitization (i.e., greater weathering of the volcaniclastic parent material). The downslope soil exhibited strong redoximorphic mottling, which was attributed to its proximity to an ancient lake. Also, the downslope soil exhibited evidence for two generations of redoximorphic features, separated by a phase of clay translocation, indicative of a shift from poorer drainage to better drainage and back to poor drainage. The changing drainage characteristics were attributed to fluctuations in lake level, among other factors (Ashley and Driese, 2000). By contrast, the upslope soil was oxidized and lacked redoximorphic features. Hence, the upslope setting was probably a drier and better-drained site than the downslope one.

Buried organic-rich or formerly organic-rich soils have figured importantly in environmental reconstructions for archaeological sites in the middle latitudes of North America. A common association of soil colors and horizons in many buried situations is a black or very dark gray A horizon, sometimes cumulic and relatively high in soil organic matter (SOM) content, over a fully reduced or mottled C or Bw horizon – Cgb or Bgb (see the entry on "Soils" in this volume). This relationship is indicative of a high water table producing the reduced zone and also promoting high rates of SOM production in the A horizon. This sort of soil profile has been reported from a wide variety of paleotopographic lows in now well-drained settings at sites throughout the central and western United States dating to the late Pleistocene and early Holocene. These buried organic-rich zones are most widely known as "black mats," but they have been referred to by other names as well – see Quade et al. (1998) and Haynes (2008) for a review of the terminology. They are not always described as soils, but they clearly represent some form of pedogenesis (accumulation of SOM on a stable land surface along with postdepositional alteration of parent material below the surface). The black mats are also clearly indicative of local environmental conditions (perhaps a "wet meadow" or bog) and may be tied to climate if a direct relationship can be shown between the local groundwater conditions and climate.

A recent study of organic-rich cumulic soils representing buried Paleoindian landscapes in the US Central Plains linked soil development to paleoclimate (Mandel, 2008). According to that study, very slow alluviation occurred between ca. 13,000 and 9000 ^{14}C yr BP because strong zonal airflow at the surface restricted the northward penetration of moist Gulf air masses into the Central Plains at that time. Weak Pacific storms depleted of Gulf moisture may have generated enough rainfall and associated runoff to promote alluviation in streams, but at a slow rate, thereby allowing organic-rich cumulative soils to develop on floodplains and alluvial fans.

Biotic evidence

As previously noted, biotic evidence consists of plant and animal remains. The most common types of plant fossils recovered as part of a geoarchaeological investigation are pollen and phytoliths. Diatoms are unicellular forms of algae, sometimes aggregated into filamentous colonies, that many classify among the Protista. They have also provided evidence for understanding environmental change in geoarchaeological studies. The animal fossil groups that are used to infer past environmental conditions consist of vertebrates (e.g., mammals, reptiles, amphibians, fish, and birds) and invertebrates (e.g., insects, mollusks, and ostracods).

Pollen

Under certain conditions, pollen and spores from plants can be preserved in sediments and soils and may be used to reconstruct paleoenvironments at and near archaeological sites (e.g., Troels-Smith, 1960; Martin, 1963; Dimbleby, 1963; Leroi-Gouran, 1965; Short, 1978; Dimbleby, 1985; Tsukada et al., 1986; Bryant and Holloway, 1996; Bakels, 2000; Roy et al., 2012). Rapp and Hill (2006, 169) noted that, "Except for certain macrofossils, pollen has probably contributed more to archaeological interpretation [of paleoenvironments] than any other plant remains."

Various objectives related to paleoenvironmental reconstruction have driven the application of palynology (the study of pollen) in archaeological investigations. In some cases, pollen analysis provided a way to determine whether certain plant resources were available within the former landscape for people to use in the past. For example, archaeological investigations at the Inuit winter settlement sites of Oakes Bay 1 in north-central Labrador included pollen and macrofossil analyses to determine if terrestrial resources such as peat and wood were available for fuel and house construction, respectively, during the Little Ice Age (AD 1500–1870) (Roy et al., 2012). Based on the pollen record, following a 2000-year period of cold and dry conditions that characterized the Neoglacial climatic episode (post Altithermal, that is, beginning around 4000 BP), the reappearance of moist-habitat plant species and the establishment of larch at ca. 1000 cal yr BP provide evidence of a return to more humid conditions that in turn triggered the onset of paludification and the formation of peat that persisted well into the Little Ice Age. Hence, Roy et al. (2012) concluded that natural resources such as trees and peat were readily available and certainly more abundant during the Little Ice Age compared to the Neoglacial.

Pollen analysis also has been used to identify episodes of regional bioclimatic change that may have (1) favored or deterred human occupation at an archaeological site or (2) brought about cultural transitions. For example, the pollen record preserved in a fen at the L'Anse Aux Meadows site in Newfoundland was used to determine whether there were significant environmental changes over the past 6000 years that may have caused episodic human occupation and abandonment of the site (Davis et al., 1988). Although the relationships between regional environmental changes (inferred from the pollen spectra) and the human response are indistinct, a cool interval soon after 2500 BP coincides with a 1000-year hiatus in occupation at the site.

In a similar study, Verkhovskaya et al. (1994) analyzed pollen in sediments at three stratified archaeological sites in the Iman River basin of eastern Russia. The pollen record spanned the past 5000 years and indicated that during the transition from the Bronze Age to the Early Iron Age, which occurred around 2500 years ago, mixed coniferous and broad-leaved trees replaced a thinning birch forest surrounding the sites. Also, the pollen data indicated that the transition was marked by a dramatic increase in moisture. Verkhovskaya et al. (1994) suggested that the environmental change occurring at ca. 2500 BP strongly influenced the changing cultural traditions in eastern Russia.

Pollen data also can serve to reconstruct changes in depositional environments at archaeological sites. A good example of this application is a study of late Holocene environmental change at the ancient Yeanri burial mound on the Gimhae fluvial plain in southern Korea (Yi and Saito, 2003). Detailed studies of palynomorphs (microscopic organic fossils that include pollen, spores, and other biotic forms) recovered from cores collected near the burial mound revealed two local pollen zones: a lower Pollen Zone I, dominated by a *Pinus-Quercus* assemblage, and an upper Pollen Zone II, dominated by a *Pinus-Quercus-Gramineae* assemblage. The pollen data, combined with an analysis of the mollusk assemblages, indicate that the depositional environments changed from a lower intertidal flat of a shallow bay environment to an upper intertidal flat in a shallow bay shortly before ca. 1300 ^{14}C BP, and then finally to a fluvial plain similar to that of today. This environmental change may have resulted from uplift along the Yangsan Fault. Later, the exposed area was modified by human activities, as indicated by a sudden increase in grassland herbaceous pollen grains. According to Yi and Saito (2003), the loss of this bay probably had a dramatic effect on the Golden Crown Gaya State (third–seventh centuries AD), which used it as a major port for regional trade; the disappearance of the bay environment may explain why it eventually merged with the Shilla State.

Phytoliths

Phytoliths, or "plant stones," are rigid, microscopic silica bodies deposited in the cell walls, cell interiors, and intracellular spaces of many plants (Piperno, 2006). Phytoliths provide structural support (increased rigidity and strength) and protection from herbivores and pathogens. Although species of many plant families produce phytoliths (Piperno, 1989), in the temperate regions of North America and Eurasia, only a few families are responsible for over 95 % of all phytoliths (Piperno, 2006). These include Poaceae (grasses), Cyperaceae, Asteraceae (Lanning and Eleuterius, 1989; Piperno, 2006), ferns, horsetails, conifers (Klein and Geis, 1978), and some deciduous trees (Geis, 1973; Bozarth, 1992). Although dicot forbs produce few diagnostic shapes of silica (Morris et al., 2009), they contribute some amorphous biogenic silica to the soils. A few families common in the temperate regions do not appear to accumulate silica (e.g., Fabaceae and Brassicaceae) and are therefore "silent" in the soil phytolith record (Blinnikov et al., 2013).

The advantages offered to geoarchaeology by phytoliths include (1) their abundance in grasses, (2) the fact that they are deposited directly into the soil, (3) their siliceous skeletons that are resistant to decay, and (4) the morphological differences they exhibit between the dominant C_3 and C_4 grass subfamilies (i.e., Chloridoideae, Panicoideae, and Pooideae). Soil phytolith assemblages have provided paleobotanical data going back hundreds to millions of years (Rovner, 1988), and as a result, phytoliths can be important paleoenvironmental proxies, especially at archaeological sites where pollen is not preserved.

Changes in phytolith assemblages throughout a soil profile may indicate shifts in local environment from warm/dry to warm/moist or cool/moist. Chloridoids are C_4 shortgrasses such as grama grass (*Bouteloua* spp.) and buffalo grass (*Buchloë dactyloides*). Chloridoids are adapted to warm/dry climates and have a diagnostic "saddle" shape, short-cell phytolith. Panicoids are C_4 tallgrasses such as switchgrass (*Panicum*), Indian grass (*Sorghastrum nutans*), big bluestem (*Andropogon gerardii*), and little bluestem (*Schizachyrium scoparium*) that are adapted to warm/moist climates. Panicoid short-cell morphotypes include cross-shapes and bilobates. Pooids are C_3 cool-season grasses that include a variety of genera such as bluegrass (*Poa*), wheatgrass (*Agropyron*), wild rye (*Elymus*), and needlegrass (*Stipa*). Pooids produce a variety of unique morphotypes that are classified as trapeziforms (Madella et al., 2005), including the *Stipa*-type lobate trapeziform identified by Fredlund and Tieszen (1994). In most cases, C_3 trees and shrubs are under-represented in the phytolith record (Fredlund and Tieszen, 1997; Piperno, 2006).

Phytolith preservation in soils and sediments is affected by bioturbation, translocation, presence of iron and aluminum oxides, erosion, fire, wind, herbivory, anthropogenic activity, soil texture and pH, rates of deposition, and exposure to water (Fredlund and Tieszen, 1997; Grave and Kealhofer, 1999; Piperno, 2006; Murphy, 2008). Also, while grasses actively collect soluble silica, other plants, such as C_3 trees and shrubs, do so passively and may produce phytoliths irregularly depending on local climate and soil conditions (Bozarth, 1992).

Combining phytolith data with stable carbon isotope values determined on pedogenic carbon (see the "Stable Carbon Isotopes in Soils" entry in this volume) can be very effective in reconstructing paleoenvironments at archaeological sites. Changes in the relative proportions of C_3 versus C_4 species inferred from the $\delta^{13}C$ values can be compared to the phytolith data, and inferences can be made about the input of carbon from C_3 trees and shrubs that are under-represented in the phytolith record (Fredlund and Tieszen, 1997; Piperno, 2006). In addition, phytolith differentiation among the major grass subfamilies allows a more refined assessment of the stable carbon isotope ($\delta^{13}C$) data. Because warm/moist and warm/dry C_4 grasses as well as cool/moist and cool/dry C_3 grasses can be differentiated based on phytolith morphotypes, more precise paleoenvironmental assessments can be made compared to using only the broad trends in stable carbon isotope values. For example, at the Beacon Island site, an Agate Basin (Paleoindian) bison kill in northwestern North Dakota, the results of phytolith analysis provided information about precipitation trends for the period of record that could not be gleaned from the $\delta^{13}C$ values determined on soil organic matter alone (Mandel et al., 2014). Based on the combined phytolith and $\delta^{13}C$ data, cool-season C_3 prairie species that prefer moist habitats dominated the site at ca. 10,300 ^{14}C yr BP, the time of the bison kill. Slight warming and drying occurred soon after ca. 10,300 ^{14}C yr BP, indicated by relatively higher $\delta^{13}C$ values determined on soil organic matter and a significant increase in phytoliths from drought-resistant *Stipa*, respectively. Phytolith and isotope data also point to a warmer and probably drier climate after ca. 8000 ^{14}C yr BP, indicated by higher $\delta^{13}C$ values and the appearance of warm-season C_4 chloridoids at the site. Hence, the Agate Basin occupation at the Beacon Island site coincided with the coolest and wettest climatic episode recorded in the sampled deposits (Mandel et al., 2014).

Phytolith analysis was combined with other proxies, including stable carbon isotopes ($\delta^{13}C$) and microscopic charcoal, to help reconstruct the vegetative history at the Kanorado locality, a cluster of three Early Paleoindian sites in northwestern Kansas (Cordova et al., 2011). Phytolith and $\delta^{13}C$ data for site 14SN106 at Kanorado show a gradual shift from C_3 plant to C_4 grass dominance, beginning with open woodland containing C_3 grasses around 14,200 cal yr BP to the modern C_4 shortgrass-dominated prairie soon after ca. 10,400 cal yr BP.

Diatoms

Diatoms are unicellular algae that occur in moist or aquatic settings and are among the most common types of phytoplankton (Battarbee, 1988). Like phytoliths, diatoms have siliceous cell walls resistant to decay and can be preserved as microfossils in sedimentary sequences. Distinct shapes provide a way to identify different species of diatoms, and the various species have specific habitat tolerances. Because diatoms are sensitive indicators of water conditions (e.g., chemistry, depth, flow, temperature, and turbidity), they are valuable paleoenvironmental proxies in certain settings.

Diatoms have been recovered from both lake and marine sediments and are especially useful in documenting environmental changes that reflect fluctuations in water levels. Diatoms can help document sea-level changes because some species are very sensitive to changes in salinity and are consequently indicators of transgression and regression sequences (Rapp and Hill, 2006, 175). Particular species are associated with freshwater, brackish, or marine conditions, and therefore, studies of diatoms can help reconstruct paleoenvironmental settings connected to coastal archaeological sites. For example, along the Baltic coast, the interaction of isostatic uplift and eustatic sea-level rise has produced a complex pattern of transgressions and regressions, all reflected in the diatom record (Smol and Stoermer, 2010), and altitudinal zonation of ancient shorelines and archaeological sites. In the area of Stockholm, Sweden, diatom analysis at Mesolithic to Medieval-age archaeological sites revealed a pattern of site abandonment and reoccupation related to oscillations of the Baltic Sea strandline (Miller and Robertsson, 1981).

Diatoms are also useful in paleoenvironmental analyses of archaeological sites associated with modern and former lakes or ponds because (1) diatoms tend to be the best preserved algal fossils in freshwater sediments and (2) the most complete preservation of whole diatom communities tends to occur in Quaternary lake and pond sediments, where 90 % or more of the assemblage survives burial and can be sampled (Round, 1981). A good example of using the diatom record to reconstruct paleoenvironments at sites in nonmarine settings is from North America's Southern High Plains. A series of deeply entrenched ephemeral streams, or draws, in that region contain a rich archaeological record spanning the past 13,000 years. Complex stratigraphic sequences consisting of alluvium, lacustrine deposits, and eolian sands occur in many of the draws (see discussion below on sedimentology of the draws). Diatom analysis was originally used to reconstruct local depositional environments at and near individual archaeological sites, including the Clovis site on Blackwater Draw (Lohman, 1935; Patrick, 1938). More recently, Winsborough (1995) conducted diatom analysis at 10 archaeological sites on the Southern High Plains, all in draws. Results of her work show that the draws experienced similar changes during the late Pleistocene and the Holocene. In particular, the diatom assemblages indicate that there was great similarity in the lacustrine and palustrine habitats in the draws during the terminal Pleistocene and early Holocene, with conditions that fluctuated between slightly brackish to much fresher water. These conditions were consistent with regional climatic changes that affected precipitation, which in turn caused fluctuating spring flow and water levels in ponds and marshes (Winsborough, 1995).

Animal remains

When using fossil vertebrate remains to reconstruct paleoenvironments, there are several factors to consider. Specifically, most large mammals have broad habitat tolerances, and consequently, they are less reliable indicators of environmental conditions. By contrast, small mammals, such as rodents, are more ecologically restricted and therefore usually more valuable for environmental reconstruction (Yalden, 2001). For example, at the Beacon Island bison-kill site in northwestern North Dakota (Mandel et al., 2014), the micromammal remains from the Agate Basin (Paleoindian) component reflect the presence of a marsh or bog-like environment. According to Falk and Semken (2012), the "Dark Faunule" micromammal assemblage, mostly consisting of voles, indicates cool, moist conditions with a high water table and a grassy substrate (either a meadow or a bog). Also, two taxa in the Dark Faunule, the red-backed vole (*Myodes* sp.) and

Ungava vole (*Phenacomys ungava*), require low shrubby vegetation; dwarf birch is preferred by both taxa. In addition, the remains of two large rodents, the American beaver (*Castor canadensis*) and common muskrat (*Ondatra zibethicus*), indicate the presence of standing water at or near the Beacon Island site (Falk and Semken, 2012). Hence, the remains of small mammals indicate that, at the time of the bison kill (ca. 10,300 ^{14}C BP), there was water in the kettle basin, which probably attracted bison to the locality.

Among invertebrates, insects are ideal for paleoenvironmental reconstruction. They comprise more than half the faunal and floral species known today, and their remains are common in many depositional contexts, including ponds, bogs, lakes (often near the margins), floodplains, caves, rockshelters, and pack-rat middens (Elias, 1994). Over the past several decades, the common occurrence of well-preserved insect fossils in many archaeological settings has been demonstrated (Elias, 1994; Elias, 1996).

Prior to 1980, insect fossil studies were applied to archaeological sites mainly in Europe, especially Great Britain (Elias, 1996). From the 1980s onward, however, many interdisciplinary North American archaeological projects included insect fossil analyses in order to reconstruct paleoenvironments – e.g., Lubbock Lake site, Texas (Elias and Johnson, 1988); Lamb Spring site, Colorado (Elias, 1986); and False Cougar Cave, Montana (Elias, 1990). Although insect fossils recovered from soils and sediments at archaeological sites have yielded useful paleoenvironmental information, insect assemblages from natural deposits adjacent to archaeological sites (pond and lake sediments, peat bogs, etc.) have helped reconstruct environmental conditions for the periods of human occupation (Elias, 1994; Elias, 1996).

Mollusks, like insects, are one of the most common types of invertebrate remains associated with archaeological sites (Preece, 2001). Mollusks include gastropods (snails) and bivalves (including clams and mussels) and occur in a variety of depositional settings, including loess; caves and rockshelters; stream, lake, and spring sediments; and marine environments. Rapp and Hill (2006, 178) stressed that several factors must be considered in reconstructing paleoenvironments from assemblages of fossil mollusks, including taphonomic processes of deposition and preservation (including the potential for mixing), the relative abundance of various types of mollusks, sampling, and identification.

An excellent example of how fossil snails can be used to reconstruct paleoenvironments is the recent geoarchaeological study by May et al. (2008) at the stratified Clary Ranch site (Late Paleonidian) in Ash Hollow valley, southwestern Nebraska. This study included a detailed analysis of the composition of deeply buried fossil snail assemblages preserved in alluvium. Between ca. 9900 and 9600 ^{14}C yr BP, aquatic snails were at their highest densities, and terrestrial snails present at that time required moist substrates in protected settings. From 9500 to 9400 ^{14}C yr BP, aquatic snails disappeared and land snails became rare, indicating that standing water was no longer present. Between ca. 9300 and 9100 ^{14}C yr BP, some species of terrestrial snails returned, and they indicate the presence of dense prairie. At the end of this last interval, many snails show evidence of burning, indicating a fire in the drainage basin. Following Late Paleoindian occupation of the Clary Ranch site at ca. 9000 ^{14}C yr BP, both snail diversity and density declined, indicating a changing regional climate toward drier conditions (May et al., 2008).

In a regional study, Rollins et al. (1987) developed criteria for the recognition of ancient El Niños using mollusks from archaeological sites along coastal South America. A combination of growth increment and stable isotope analyses indicated that elevated sea surface temperatures during large-scale El Niños leave a record decodable from the growth patterns of selected bivalve shells. They concluded that these methods can be used to recognize some of the major culturally disruptive El Niño events in the geoarchaeological record, especially if ancillary information, such as faunal distribution patterns, is also considered. They also note that chances of discovery of major El Niño perturbations in the geoarchaeological record of shell middens is enhanced by the catastrophic nature of such events, and by the indication that major El Niños have a high probability of being closely spaced in time.

Bibliography

Aguado, E., and Burt, J. E., 1999. *Understanding Weather and Climate*. Upper Saddle River: Prentice Hall.

Alexandrovskiy, A. L., 2000. Holocene development of soils in response to environmental changes: the Novosvobodnaya archaeological site, North Caucasus. *Catena*, **41**(1–3), 237–248.

Ashley, G. M., 2001. Archaeological sediments in springs and wetlands. In Stein, J. K., and Farrand, W. R. (eds.), *Sediments in Archaeological Context*. Salt Lake City: University of Utah Press, pp. 183–210.

Ashley, G. M., and Driese, S. G., 2000. Paleopedology and paleohydrology of a volcaniclastic paleosol interval: implications for early Pleistocene stratigraphy and paleoclimate record, Olduvai Gorge, Tanzania. *Journal of Sedimentary Research*, **70**(5), 1065–1080.

Ashley, G. M., Tactikos, J. C., and Owen, R. B., 2009. Hominin use of springs and wetlands: paleoclimate and archaeological records from Olduvai Gorge (~1.79–1.74 Ma). *Palaeogeography Palaeoclimatology Palaeoecology*, **272** (1–2), 1–16.

Bakels, C. C., 2000. Pollen diagrams and prehistoric fields: the case of Bronze Age Haarlem, the Netherlands. *Review of Palaeobotany and Palynology*, **109**(3–4), 205–218.

Battarbee, R. W., 1988. The use of diatom analysis in archaeology: a review. *Journal of Archaeological Science*, **15**(6), 621–644.

Bettis, E. A., III, 1988. Pedogenesis in late prehistoric Indian mounds, upper Mississippi valley. *Physical Geography*, **9**(3), 263–279.

Bettis, E. A., III, Milius, A. K., Carpenter, S. J., Larick, R., Zaim, Y., Rizal, Y., Ciochon, R. L., Tassier-Surine, S. A., Murray, D., Suminto, and Bronto, S., 2009. Way out of Africa: early Pleistocene paleoenvironments inhabited by *Homo erectus* in Sangiran, Java. *Journal of Human Evolution*, **56**(1), 11–24.

Birkeland, P. W., 1984. *Soils and Geomorphology*, 2nd edn. New York: Oxford University Press.
Birkeland, P. W., 1999. *Soils and Geomorphology*, 3rd edn. New York: Oxford University Press.
Blinnikov, M. S., Bagent, C. M., and Reyerson, P. E., 2013. Phytolith assemblages and opal concentrations from modern soils differentiate temperate grasslands of controlled composition on experimental plots at Cedar Creek, Minnesota. *Quaternary International*, **287**, 101–113.
Blockley, S. P. E., Candy, I., and Blockley, S. M., 2012. Testing the role of climate change in human evolution. In Matthews, J. A. (ed.), *The SAGE Handbook of Environmental Change*. Los Angeles: Sage, Vol. 2, pp. 301–327.
Bozarth, S. R., 1992. Classification of opal phytoliths formed in selected dicotyledons native to the Great Plains. In Rapp, G. R., Jr., and Mulholland, S. C. (eds.), *Phytolith Systematics. Emerging Issues*. New York: Plenum. Advances in Archeological and Museum Science, Vol. 1, pp. 193–214.
Brown, A. G., 1997. *Alluvial Geoarchaeology: Floodplain Archaeology and Environmental Change*. Cambridge: Cambridge University Press.
Bryant, V. M., Jr., and Holloway, R. G., 1996. Archaeological palynology. In Jansonius, J., and McGregor, D. C. (eds.), *Palynology: Principles and Applications*. Salt Lake City: American Association of Stratigraphic Palynologists Foundation, Vol. 3, pp. 913–917.
Butzer, K. W., 1964. *Environment and Archaeology: An Introduction to Pleistocene Geography*. Chicago: Aldine.
Butzer, K. W., 1971. *Environment and Archaeology: An Ecological Approach to Prehistory*. Chicago: Aldine.
Cordova, C. E., Johnson, W. C., Mandel, R. D., and Palmer, M. W., 2011. Late Quaternary environmental change inferred phytoliths and other soil-related proxies: case studies from the central and southern Great Plains, USA. *Catena*, **85**(2), 87–108.
Cremeens, D. L., 1995. Pedogenesis of Cotiga Mound, a 2100-year-old Woodland mound in southwest West Virginia. *Soil Science Society of America Journal*, **59**(5), 1377–1388.
Davis, A. M., McAndrews, J. H., and Wallace, B. L., 1988. Paleoenvironment and the archaeological record at the L'Anse Aux Meadows Site, Newfoundland. *Geoarchaeology*, **3**(1), 53–64.
de Maigret, A., Azzi, C., Marcolongo, B., and Palmieri, A. M., 1989. Recent pedogenesis and neotectonics affecting archaeological sites in North Yemen. *Paléorient*, **15**(1), 239–243.
Dimbleby, G. W., 1963. Pollen analysis of a Mesolithic site at Addington, Kent. *Grana Palynologica*, **4**(1), 140–148.
Dimbleby, G. W., 1985. *The Palynology of Archaeological Sites*. London: Academic.
Dincauze, D. F., 2000. *Environmental Archaeology: Principles and Practice*. Cambridge: Cambridge University Press.
Elias, S. A., 1986. Fossil insect evidence for late Pleistocene paleoenvironments of the Lamb Spring site, Colorado. *Geoarchaeology*, **1**(4), 381–387.
Elias, S. A., 1990. The timing and intensity of environmental changes during the Paleoindian period in western North America: evidence from the insect fossil record. In Agenbroad, L. D., Mead, J. I., and Nelson, L. W. (eds.), *Megafauna and Man: Discovery of America's Heartland*. Hot Springs, SD: The Mammoth Site of Hot Springs, South Dakota, Inc, pp. 11–14.
Elias, S. A., 1994. *Quaternary Insects and their Environments*. Washington, DC: Smithsonian Press.
Elias, S. A., 1996. Insect fossil evidence on late Wisconsinan environments of the Bering Land Bridge. In West, F. H. (ed.), *American Beginnings: The Prehistory and Paleoecology of Beringia*. Chicago: University of Chicago Press, pp. 110–118.
Elias, S. A., and Johnson, E., 1988. Pilot study of fossil beetles at the Lubbock Lake Landmark. *Current Research in the Pleistocene*, **5**, 57–59.
Falk, C. R., and Semken, H. A., Jr., 2012. Paleoenvironmental context: the local fauna record. In Mitchell, M. D. (ed.), *Agate Basin Archaeology at Beacon Island, North Dakota*. Arvada, CO: PaleoCultural Research Group. Paleocultural Research Group, Research Contribution 86. Prepared for the State Historical Society of North Dakota, pp. 171–181.
Fedele, F. G., 1990. Man, land and climate: emerging interactions from the Holocene of the Yemen Highlands. In Bottema, S., Entjes-Nieborg, G., and van Zeist, W. (eds.), *Man's Role in the Shaping of the Eastern Mediterranean Landscape*. Rotterdam: A. A. Balkema, pp. 31–42.
Ferring, C. R., 1986. Rates of fluvial sedimentation: implications for archaeological variability. *Geoarchaeology*, **1**(3), 259–274.
Ferring, C. R., 2001. Geoarchaeology in alluvial landscapes. In Goldberg, P., Holliday, V. T., and Ferring, C. R. (eds.), *Earth Sciences and Archaeology*. New York: Kluwer/Plenum, pp. 77–106.
Fredlund, G. G., and Tieszen, L. L., 1994. Modern phytolith assemblages from the North American Great Plains. *Journal of Biogeography*, **21**(3), 321–335.
Fredlund, G. G., and Tieszen, L. L., 1997. Calibrating grass phytolith assemblages in climatic terms: application to late Pleistocene assemblages from Kansas and Nebraska. *Palaeogeography Palaeoclimatology Palaeoecology*, **136**(1–4), 199–211.
Gabunia, L., Vekua, A., and Lordkipandize, D., 2000. The environmental contexts of early human occupation of Georgia (Transcaucasia). *Journal of Human Evolution*, **38**(6), 785–802.
Geis, J. W., 1973. Biogenic silica in selected species of deciduous angiosperms. *Soil Science*, **116**(2), 113–119.
Grave, P., and Kealhofer, L., 1999. Assessing bioturbation in archaeological sediments using soil morphology and phytolith analysis. *Journal of Archaeological Science*, **26**(10), 1239–1248.
Haynes, C. V., Jr., 1975. Pleistocene and recent stratigraphy. In Wendorf, F., and Hester, J. J. (eds.), *Late Pleistocene Environments of the Southern High Plains*. Taos, NM: Ft. Burgwin Research Center. Ft. Burgwin Research Center, Publication 9, pp. 59–96.
Haynes, C. V., Jr., 1995. Geochronology and paleoenvironmental change, Clovis type site, Blackwater Draw, New Mexico. *Geoarchaeology*, **10**(5), 317–388.
Haynes, C. V., Jr., 2008. Younger Dryas "black mats" and the Rancholabrean termination in North America. *Proceedings of the National Academy of Sciences*, **105**(18), 6520–6525.
Haynes, C. V., Jr., and Agogino, G. A., 1966. Prehistoric springs and geochronology of the Clovis site, New Mexico. *American Antiquity*, **31**(6), 812–821.
Haynes, C. V., Jr., and Warnica, J. M., 2012. *Geology, Archaeology and Climate Change at Blackwater Draw, New Mexico: F. Earl Green and the Geoarchaeology of the Clovis Type Site*. Portales, NM: Eastern New Mexico University. Contributions in Anthropology 15.
Holliday, V. T., 1985. Archaeological geology of the Lubbock Lake site, Southern High Plains of Texas. *Geological Society of America Bulletin*, **96**(12), 1483–1492.
Holliday, V. T., 1995. *Stratigraphy and Paleoenvironments of Late Quaternary Valley Fills on the Southern High Plains*. Boulder, CO: The Geological Society of America. GSA Memoir 186.
Holliday, V. T., 1997. *Paleoindian Geoarchaeology of the Southern High Plains*. Austin, TX: University of Texas Press.
Holliday, V. T., 2004. *Soils in Archaeological Research*. Oxford: Oxford University Press.
Holliday, V. T., Hoffecker, J. F., Goldberg, P., Macphail, R. I., Forman, S. L., Anikovich, M., and Sinitsyn, A., 2007.

Geoarchaeology of the Kostenki-Borshchevo sites, Don River Valley, Russia. *Geoarchaeology*, **22**(2), 181–228.

Jenny, H., 1941. *Factors of Soil Formation; A System of Quantitative Pedology*. New York: McGraw-Hill.

Klein, R. L., and Geis, J. W., 1978. Biogenic silica in the Pinaceae. *Soil Science*, **126**(3), 145–156.

Lanning, F. C., and Eleuterius, L. N., 1989. Silica deposition in some C_3 and C_4 species of grasses, sedges and composites in the USA. *Annals of Botany*, **64**(4), 395–410.

Leighton, M. M., 1933. Some observations on the antiquity of man in Illinois. *Transactions of the Illinois State Academy of Sciences*, **25**, 83.

Leroi-Gouran, A., 1965. Les analyses polliniques sur les sédiments des grottes. *Bulletin de l'Association français pour l'Étude du Quaternaire*, **2**(2), 145–152.

Lohman, K. E., 1935. Diatoms from Quaternary lake beds near Clovis, New Mexico. *Journal of Paleontology*, **9**(5), 455–459.

Madella, M., Alexandre, A., and Ball, T., 2005. International Code for Phytoloth Nomenclature 1.0. *Annals of Botany*, **96**(2), 253–260.

Mandel, R. D., 2006. The effects of late Quaternary landscape evolution on the archaeology of Kansas. In Hoard, R. J., and Banks, W. E. (eds.), *Kansas Archaeology*. Lawrence, KS: University Press of Kansas, pp. 46–75.

Mandel, R. D., 2008. Buried Paleoindian-age landscapes in stream valleys of the central plains, USA. *Geomorphology*, **101**(1–2), 342–361.

Mandel, R. D., and Hofman, J. L., 2003. Geoarchaeological investigations at the Winger site: a Late Paleoindian bison bonebed in southwestern Kansas, U.S.A. *Geoarchaeology*, **18**(1), 129–144.

Mandel, R. D., and Simmons, A. H., 2001. Prehistoric occupation of Late Quaternary landscapes near Kharga Oasis, Western Desert of Egypt. *Geoarchaeology*, **16**(1), 95–117.

Mandel, R. D., Murphy, L. R., and Mitchell, M. D., 2014. Geoarchaeology and paleoenvironmental context of the Beacon Island site, an Agate Basin (Paleoindian) bison kill in northwestern North Dakota, USA. *Quaternary International*, **342**, 91–113.

Martin, P. S., 1963. *The Last 10,000 Years: A Fossil Pollen Record of the American Southwest*. Tucson, AZ: University of Arizona Press.

May, D. W., Hill, M. G., Holven, A. C., Loebel, T. J., Rapson, D. J., Semken, H. A., Jr., and Theler, J. L., 2008. Geoarchaeology of the Clary Ranch Paleoindian sites, western Nebraska. In Raynolds, R. G. (ed.), *Roaming the Rocky Mountains and Environs: Geological Field Trips*. Boulder, CO: The Geological Society of America. GSA Field Guide 10, pp. 265–293.

Miller, U., and Robertsson, A. M., 1981. Current biostratigraphical studies connected with archaeological excavations in the Stockholm region. *Striae*, **14**, 167–173.

Moody, U. L., and Dort, W., Jr., 1990. Microstratigraphic analysis of sediments and soils; Wasden archaeological site, eastern Snake River Plain, Idaho. In Lasca, N. P., and Donahue, J. (eds.), *Archaeological Geology of North America*. Boulder, CO: The Geological Society of America. GSA Centennial Volume, Vol. 4, pp. 361–382.

Morris, L. R., Baker, F. A., Morris, C., and Ryel, R. J., 2009. Phytolith types and type-frequencies in native and introduced species of the sagebrush steppe and pinyon-juniper woodlands of the Great Basin, USA. *Review of Palaeobotany and Palynology*, **157**(3–4), 339–357.

Murphy, L. R., 2008. Geoarchaeology of the Burntwood Creek Rockshelter (14RW418), Northwest Kansas. Unpublished master's thesis, University of Kansas, Lawrence, KS

Overstreet, W. C., and Grolier, M. J., 1988. Reconnaissance geology of the al-Jubah quadrangle, Yemen Arab Republic. In Overstreet, W. C., Grolier, M. J., and Toplyn, M. R. (eds.), *Geological and Archaeological Reconnaissance in the Yemen Arab Republic, 1985*. Washington, DC: American Foundation for the Study of Man, pp. 155–288.

Patrick, R., 1938. The occurrence of flints and extinct animals in pluvial deposits near Clovis, New Mexico. Part V: Diatom evidence from the gravel pit. *Proceedings of the Philadelphia Academy of Natural Sciences*, **90**, 15–24.

Piperno, D. R., 1989. The occurrence of phytoliths in the reproductive structures of selected tropical angiosperms and their significance in tropical paleoecology, paleoethnobotany and systematics. *Review of Paleobotany and Palynology*, **61**(1–2), 147–173.

Piperno, D. R., 2006. *Phytoliths: A Comprehensive Guide for Archaeologists and Paleoecologists*. Lanham, MA: AltaMira Press.

Preece, R. C., 2001. Non-marine mollusca and archaeology. In Brothwell, D. R., and Pollard, A. M. (eds.), *Handbook of Archaeological Sciences*. Chichester, UK: Wiley, pp. 134–145.

Quade, J., Forester, R. M., Pratt, W. L., and Carter, C., 1998. Black mats, spring-fed streams, and late-glacial-age recharge in the southern Great Basin. *Quaternary Research*, **49**(2), 129–148.

Rapp, G. R., Jr., and Hill, C. L., 2006. *Geoarchaeology: The Earth Science Approach to Archaeological Interpretation*, 2nd edn. New Haven: Yale University Press.

Reider, R. G., 1980. Late Pleistocene and Holocene soils of the Carter/Kerr-McGee archeological site, Powder River Basin, Wyoming. *Catena*, **7**(4), 301–315.

Reider, R. G., 1982a. Soil development and paleoenvironments. In Frison, G. C., and Stanford, D. J. (eds.), *The Agate Basin Site: A Record of Paleoindian Occupation of the Northwestern High Plains*. New York: Academic, pp. 331–344.

Reider, R. G., 1982b. The soil of Clovis age at the Sheaman archaeological site, eastern Wyoming. *University of Wyoming Contributions to Geology*, **21**(2), 195–200.

Reider, R. G., 1990. Late Pleistocene and Holocene pedogenic and environmental trends at archaeological sites in plains and mountain areas of Colorado and Wyoming. In Lasca, N. P., and Donahue, J. (eds.), *Archaeological Geology of North America*. Boulder, CO: The Geological Society of America. GSA Centennial Special Volume, Vol. 4, pp. 335–360.

Rollins, H. B., Sandweiss, D. H., Brand, U., and Rollins, J. C., 1987. Growth increment and stable isotope analysis of marine bivalves: implications for the geoarchaeological record of El Niño. *Geoarchaeology*, **2**(3), 181–197.

Round, F. E., 1981. *The Ecology of Algae*. Cambridge: Cambridge University Press.

Rovner, I., 1988. Macro- and micro-ecological reconstruction using plant opal phytolith data from archaeological sediments. *Geoarchaeology*, **3**(2), 155–163.

Roy, N., Bhiry, N., and Woollett, J., 2012. Environmental change and terrestrial resource use by the Thule and Inuit of Labrador, Canada. *Geoarchaeology*, **27**(1), 18–33.

Sandor, J. A., 1992. Long-term effects of prehistoric agriculture on soils: examples from New Mexico and Peru. In Holliday, V. T. (ed.), *Soils in Archaeology: Landscape Evolution and Human Occupation*. Washington, DC: Smithsonian Institution Press, pp. 217–245.

Short, S. K., 1978. Holocene Palynology in Labrador-Ungava: Climatic History and Cultural Changes on the Central Coast. Unpublished Ph.D. dissertation, Department of Anthropology, University of Colorado, Boulder.

Smol, J. P., and Stoermer, E. F., 2010. *The Diatoms: Applications for the Environment and Earth Sciences*, 2nd edn. Cambridge: Cambridge University Press.

Troels-Smith, J., 1960. *The Muldbjerg Dwelling Place: An Early Neolithic Archeological Site in the Aamosen Bog, West-Zealand,*

Denmark. From The Smithsonian Report for 1959. Washington, DC: Smithsonian Institute, pp. 577–601.
Tsukada, M., Sugita, S., and Tsukada, Y., 1986. Oldest primitive agriculture and vegetational environments in Japan. *Nature*, **322**(6080), 632–634.
Verkhovskaya, N. B., Kundyshev, A. S., and Kliuev, N. A., 1994. Bronze-Early Iron Age environment of the Iman River basin, Russian Far East. *Geoarchaeology*, **9**(6), 503–513.
Wilkinson, T. J., 1997. Holocene environments of the high plateau, Yemen. Recent geoarchaeological investigations. *Geoarchaeology*, **12**(8), 833–864.
Winsborough, B. M., 1995. Diatoms. In Holliday, V. T. (ed.), *Stratigraphy and Paleoenvironments of Late Quaternary Valley Fills on the Southern High Plains*. Boulder, CO: The Geological Society of America. Geological Society of America Memoir 186, pp. 67–82.
Yaalon, D. H., 1971. Criteria for the recognition and classification of paleosols. In Yaalon, D. H. (ed.), *Paleopedology: Origin, Nature and Dating of Paleosols*. Jerusalem: International Society of Soil Science and Israel Universities Press, pp. 153–158.
Yalden, D., 2001. Mammals as climatic indicators. In Brothwell, D. R., and Pollard, A. M. (eds.), *Handbook of Archaeological Sciences*. Chichester, UK: Wiley, pp. 147–154.
Yi, S., and Saito, Y., 2003. Palynological evidence for late Holocene environmental change on the Gimhae fluvial plain, southern Korean Peninsula: Reconstructing the rise and fall of Golden Crown Gaya State. *Geoarchaeology*, **18**(8), 831–850.

Cross-references

Alluvial Settings
Great Plains Geoarchaeology
Sedimentology
Site Formation Processes
Soils
Spring Settings
Stable Carbon Isotopes in Soils
Stratigraphy

PALEOMAGNETISM

Josep M. Parés
Geochronology Program, CENIEH, Burgos, Spain

Definition

Ferromagnetic minerals. Minerals that give rise to a magnetic field in the absence of an applied field.

Magnetostratigraphy or *magnetic stratigraphy*. The pattern of polarity zones in stratigraphic sequences.

Paleomagnetism. History of the Earth's magnetic field as recorded in rocky materials.

Relaxation time. The time (τ) over which magnetic remanence will decay to 1/e of its initial value.

Virtual geomagnetic pole. The geographic point where the axis of the Earth's magnetic dipole intersects the surface of the Earth.

Introduction

More than 400 years ago, William Gilbert concluded "magnus magnes ipse est globus terrestris," meaning that the Earth itself is a giant magnet. Several centuries of studies on geomagnetism, followed by investigations into paleomagnetism, have led to present-day knowledge of the geomagnetic field's behavior and the properties and intricacies of remanent, or fossil, magnetism in rocky materials. In addition, by studying the paleomagnetic record, it has been possible not only to improve our understanding of the long-term structure and temporal change of the geomagnetic field but also to develop the geomagnetic polarity time scale, or GPTS (e.g., Cande and Kent, 1995), archaeomagnetic curves (Tanguy et al., 2003; Pavón-Carrasco et al., 2009, 2010; Hagstrum and Blinman, 2010), relative paleointensity curves (Guyodo and Valet, 1999; Valet et al., 2005; Channell et al., 2009), and geomagnetic excursion records (e.g., Channell et al., 2002, 2012; Thouveny et al., 2004; Laj and Channell, 2007) in order to construct better chronological sequences.

The fundamental assumptions of paleomagnetism are as follows. (1) Rocky materials record the Earth's magnetic field, i.e., they become magnetized during their formation (primary magnetization) or at a subsequent time (secondary magnetization). (2) The time-averaged paleomagnetic field is produced by a geocentric axial dipole (GAD), so the calculated paleomagnetic pole coincides with the paleogeographic axis over a few thousand years.

Rocks, sediments, soil, and the majority of archaeological artifacts contain traces of ferromagnetic minerals that possess a magnetization aligned with the Earth's magnetic field. They therefore act as fossil compasses that record the Earth's magnetic field of the past. The most common ferromagnetic minerals include magnetite (Fe_3O_4), hematite (Fe_2O_3), goethite (α-FeOOH), and some iron sulfides (e.g., greigite, Fe_3S_4). A number of experiments and observations have proved that igneous and sedimentary rocks acquire an initial or primary magnetization during or shortly after formation, which is statistically aligned with the Earth's field direction. The geomagnetic field keeps changing over time, both in intensity or strength and in polarity (wherein the field reverses itself, and magnetic north reestablishes itself toward the southern geographic pole). It is possible to use such changes to assign an age to rocks, sediments, or archaeological artifacts, by comparing the observations to reference curves.

Mechanisms of natural remanence acquisition

Thermal remanent magnetization (TRM)

When a rock or object of pottery is heated above the Curie temperature (temperature at which ferromagnetism is lost) of its constituent ferromagnetic minerals – e.g., magnetite (578 °C) or hematite (680 °C) – thermal energy dominates the system. As the temperature in the system continues to cool, the thermal energy will decrease until the magnetic energy becomes large enough to block, or fix, the magnetization in the direction of the ambient field at that time.

At this stage, the magnetization M is effectively blocked so that the rock or artifact acquires a thermal remanent magnetization (TRM), and the relaxation time – the time (τ) for the remanence to decay to 1/e of its initial value – increases dramatically. The two-part corollary is that (a) an assemblage of grains with TRM will display a remanence which is parallel to the orientation of the Earth's magnetic field, and (b) the magnitude of the TRM should be proportional to the intensity of the Earth's magnetic field that was present during the moment of cooling.

Detrital remanent magnetization (DRM)

Numerous studies (see Tauxe and Kent, 1984) have examined the behavior of magnetic particles being deposited in water. As opposed to the thermal remanent magnetization mechanism, detrital grains in sedimentary environments are already magnetized, and during deposition, such magnetic particles can become physically aligned with the ambient magnetic field of the Earth. In reality, however, there are other forces besides the Earth's magnetic field competing to orient the grains, including turbulent motions of the water, viscous drag, gravitational effects when the grain strikes the bottom of the water body, and others, so that only a fraction of the grains align with the direction of the prevailing field. Processes such as consolidation, bioturbation, compaction, etc. occur following initial deposition, and these can also affect the final grain orientation. As a result, the process of magnetic acquisition in sedimentary environments should be viewed as a continuum which includes depositional and postdepositional influences (Tauxe, 2010).

Chemical remanent magnetization (CRM)

Grains in sediments can acquire a chemical remanent magnetization (CRM) by growth from zero initial volume (authigenesis) or by diagenetic alteration of preexisting minerals (e.g., weathering). Either way, during growth, grains acquire a stable remanent magnetization at a given *blocking volume*, that is, the volume at which a given magnetic grain experiences a dramatic increase in relaxation time (τ) and thus records the environmental magnetic field, just as with TRM. CRM is a very important acquisition mechanism in sediments because magnetic minerals can grow during diagenesis. If CRM is acquired long after sediment deposition, it is then a secondary remanence.

Viscous remanent magnetization (VRM)

Rocky materials very often contain "unstable" grains, i.e., they can realign to a new magnetic field after a geologically short time. The time period in which such realignment occurs is related to the relaxation time (τ). Grains with shorter τ can acquire a VRM, which is a form of secondary magnetization. The magnitude of VRM can be significant compared to the primary magnetization, and it has been detected in a vast number of materials.

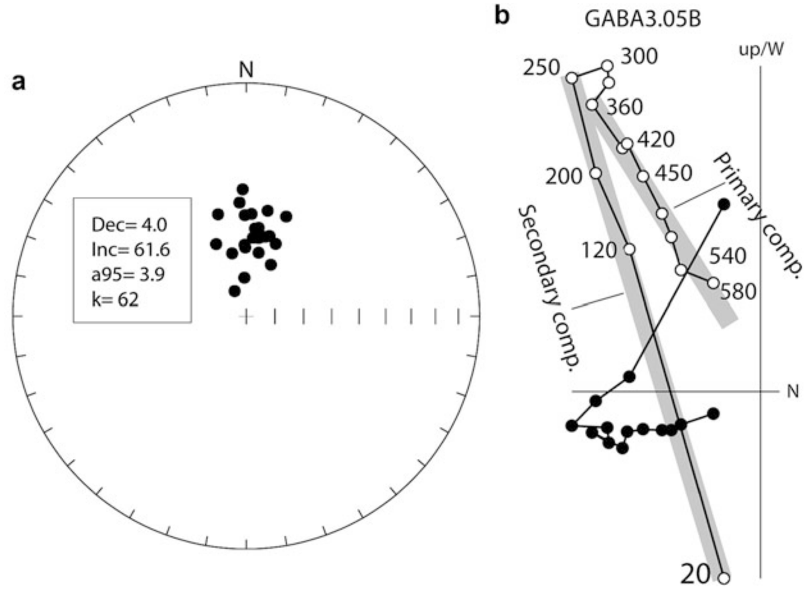
The effect of viscous magnetization can be removed by thermal demagnetization and often by alternating field demagnetization, but it can sometimes mask the primary magnetization. VRM in rocks is typically parallel to the present-day field, which can be a useful clue in its identification.

Sampling procedures

The sampling scheme in paleomagnetism varies depending on whether the study is for magnetostratigraphy (relatively spaced sampling), secular variation (narrow sampling in order to observe short-scale variations of the paleomagnetic field), or paleointensity. In magnetostratigraphic studies, the goal is to characterize the record of the Earth's magnetic field at different stratigraphic intervals through time, and sampling is designed to eliminate secular variation effects, to average errors involved in the sampling and measuring processes, and to assess the reliability of the recording medium (e.g., rock, soil, pottery). Consequently, the desired sampling resolution for magnetostratigraphy is established by the estimated sedimentation rate, and three independently oriented *samples* (N) are generally taken at each *site* (= horizon or stratum), so that the polarity can be characterized unambiguously and site statistics determined. Note that in magnetostratigraphy, sampling is broadly applied to avoid the variability from "paleomagnetic noise," whereas in secular variation studies, this is precisely the goal, and more samples per site are taken than would be the case for magnetostratigraphy to maximize the capture of detailed variations in the paleomagnetic record (e.g., Lanos, 2004; Kovacheva et al., 2009). Generally, eight specimens are considered minimally adequate (e.g., Eighmy and Sternberg, 1990), as only very small increases in precision are achieved beyond ten specimens (Tarling, 1971).

When sampling, it is often necessary to excavate a pit to obtain unweathered material using a pick mattock, spade, or similar tool, and then a vertical face can be fashioned in firmly consolidated sediment using a scraper or hacksaw blade to yield a fist-sized sample. Soft, non-cohesive clay and silty deposits can be sampled by hammering a brass tube with a reinforced stainless steel tip into the cleaned outcrop surface at a given angle. Alternatively, block samples carved from an outcrop can be obtained in the field. When dealing with soft sediments, it is useful to impregnate with a solution of sodium or ethyl silicate and water (1:1) for solidification. In cohesive, hard materials, a portable drilling machine, equipped with a -water-cooled diamond nonmagnetic drill bit, is typically used.

In all cases, samples need to be carefully oriented in the field with the help of a magnetic compass (or sun compass for strongly magnetic rocks, i.e., basalts) and a level.



Paleomagnetism, Figure 1 (**a**) Equal-area projection of the characteristic remanent magnetization (*ChRM*) directions. Each *dot* on the stereographic projection corresponds to an individual sample. Symbols are projections onto the lower hemisphere and thus correspond to samples with normal polarity (Data from the northern hemisphere). Particulars of the mean paleomagnetic directions are shown (*Dec* declination, *Inc* inclination, $\alpha_{95} = 95$ % confidence circle radius, k = precision (Fisher) parameter). (**b**) Example of an orthogonal projection diagram, also known as Zijderveld diagram. Solid (*open*) data points represent vector end points projected onto the *horizontal* (*vertical*) plane. Numbers adjacent to data points are demagnetization levels (Celsius degrees in this example). *Thick lines* show the primary (*ChRM*) and secondary magnetization directions identified in the sample.

Primary and secondary magnetizations: demagnetization procedures

In addition to their primary magnetization (TRM, DRM, CRM), rocky materials can acquire secondary magnetizations, which result from natural processes such as weathering, heating for an extended time, diagenesis, etc. In addition, materials can be artificially magnetized by proximity to strong magnetic fields during sampling, drilling, transportation, etc. One of the major tasks in paleomagnetism involves resolving the natural remanent magnetization (NRM) – i.e., the sum of all magnetizations carried by a rock – into its components, primary and secondary.

Alternating field demagnetization

In order to isolate and retrieve the primary remanence, specimens are subjected to *progressive demagnetization* or magnetic cleaning in the laboratory. The underlying principle is that minerals carrying a secondary magnetization are magnetically "softer," or put in different words, they have shorter relaxation times. Several methods are routinely used to clean or demagnetize the samples. *Coercivity* can be defined as the critical field strength to realign the magnetization of a grain. The so-called alternating field (AF) demagnetization is based on an oscillating field (the demagnetizing field) which is smoothly reduced to zero in the absence of any external field. Because of the alternating nature of the demagnetizing field, and the application of progressively increasing peak demagnetizing fields, grains with coercivities lower than the peak field will realign their remanence back and forth and will be frozen half along one direction and half along the opposite. As a result, the net contribution to the remanence will be zero. In practice, the demagnetizing field – typically a peak field of around 200 mT (milliteslas) – is applied along several orthogonal directions, or else the specimen is "tumbled" relative to the AF field.

Thermal demagnetization

The time required for the magnetization of a grain to decay in a field-free space (lacking a magnetic field) is a function of temperature. The temperature at which the magnetization of a grain becomes unlocked is called the unblocking temperature. In contrast, when an igneous rock is cooled from a melt and temperature falls below the Curie point, the remanence becomes blocked and any ambient field orientation is fixed. *Thermal demagnetization* is based on a similar principle: samples are heated to progressively higher temperatures and then allowed to cool in a field-free space. As temperature is increased stepwise, the magnetization of grains with blocking temperatures lower than that reached will be randomized. The precise unblocking temperature of grains will depend on volume, domain state (single domain or multidomain), and composition, and commonly it is a few tens of degrees below the Curie temperature.

Adequate analysis of the NRM components usually requires progressive demagnetization at a minimum of eight levels (temperature or AF peak field). The laboratory routine involves measuring the NRM and then subjecting the sample to increasingly higher demagnetization steps. The remanent magnetization is measured after each step until the most stable magnetization component is isolated; this is known as characteristic remanent magnetization (ChRM).

Display of NRM

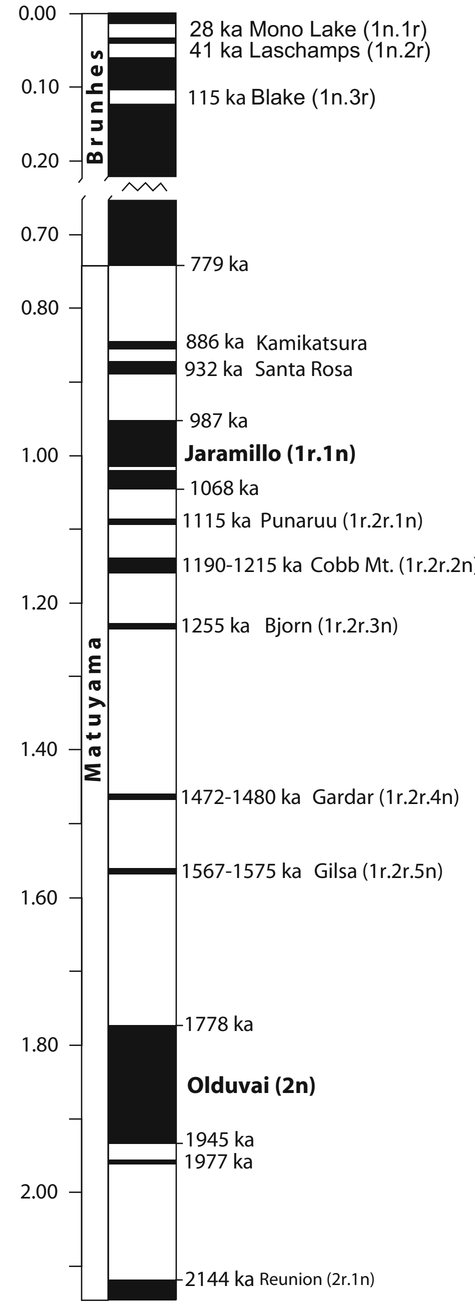
The magnetization of a rock sample is given by three values: the angles of declination (Dec) and inclination (Inc) and the intensity (J). Declination is an angle measured in the horizontal plane and ranging from 0 to 360°, and inclination is the angle in the vertical plane between the magnetic direction and the horizontal. Stereographic, lower-hemisphere equal-area projections are typically used to display NRM directions and mean ChRM directions (Figure 1a). Statistics are normally based on a probability density function (Fisher statistics), which provides the mean direction (Dec, Inc) for a given site (group of samples), the associate angle α_{95} between the unit vector and the true direction, and *k*, a precision parameter (for details and related software, see Tauxe, 2010).

Progressive demagnetization graphical display is usually done with the help of orthogonal projection diagrams, originally introduced by As and Zijderveld (1958). Such diagrams, commonly called "Zijderveld diagrams," have the power of displaying directional and intensity information on a single diagram by projecting the vector onto two orthogonal planes (also see Butler, 1992) (Figure 1b).

Magnetic reversal stratigraphy

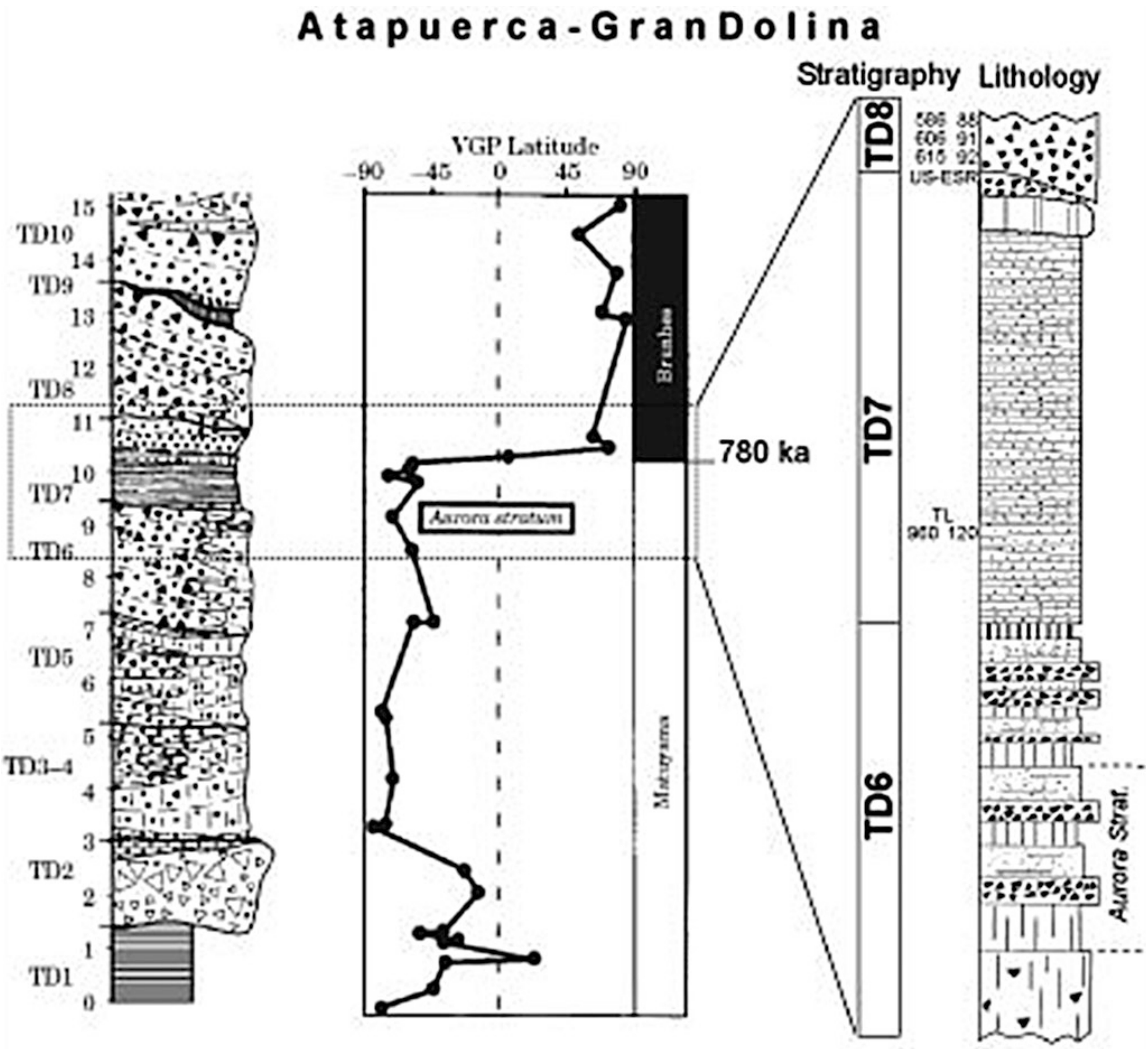
One of the most extended applications of paleomagnetism to geoarchaeology is the use of magnetic reversals to constrain the age of deposits. It is generally accepted that a reversal of the Earth's magnetic field is a global, 180° change in the geocentric axial dipole field averaged over a few thousand years (e.g., Merrill et al., 1996). The polarity (normal or reverse) of the field in a given record is therefore provided by the VGP (virtual geomagnetic pole) position, which represents a snapshot in time. A VGP can then be regarded as the paleomagnetic analog of the present-day geomagnetic pole. For a given stratigraphic profile, the variation in VGP is expressed as VGP latitude as a function of depth or stratigraphic height, where values close to +90 denote normal polarity and close to −90 denote reverse polarity. It is customary to represent the polarity as black (normal) and white (reverse) bar diagrams (see Opdyke and Channell, 1996).

In "old" archaeological contexts (Middle Pleistocene and earlier), magnetic reversal stratigraphy is very often the preferred initial means of age dating. For example, the Lower-Middle Pleistocene boundary, as marked by the Matuyama-Brunhes boundary at 780 ka, has been used in a number of archaeological sites (e.g., Parés and Pérez-



Paleomagnetism, Figure 2 Geomagnetic polarity time scale (*GPTS*) for the past ~2 Ma (Data from Cande and Kent, 1995; Channell et al., 2002, 2012).

González, 1995; Verosub et al., 1998; Oms et al., 2000; Parés et al., 2006, 2010). Magnetostratigraphy has provided major advancements in the chronology of East African localities (e.g., Tamrat et al., 1996; Lepre and Kent, 2010). In addition to the major reversals, a plethora of short polarity intervals (SPI) and some geomagnetic excursions (often regional departures of the geomagnetic



Paleomagnetism, Figure 3 Summary of the magnetostratigraphy and chronology for TD6 through the lower TD8 stratigraphic layers at Gran Dolina, Atapuerca. *Left* side of the figure shows the existing paleomagnetic and stratigraphic data (Modified from Parés and Pérez-González, 1999), and to the *right* is an enlargement (Lithology is modified from Bermúdez de Castro et al., 2008). US-ESR ages from Falguères et al. (1999) and TL ages from Berger et al. (2008).

pole and/or changes in geomagnetic intensity with durations limited to tens of thousands of years or less) have been described in the upper part of the Matuyama and Brunhes Chrons (Channell et al., 2002, 2012) (Figure 2), which also have potential for age determination.

The TD6 level at Atapuerca Gran Dolina (northern Spain) provides an excellent example of magnetostratigraphic dating of an archaeological horizon with applications for hominin paleoanthropology. The infilling sediments at Gran Dolina cave, more than 15 m thick, were originally studied for paleomagnetism by Parés and Pérez-Gonzalez (1995, 1999), and reversed magnetization provided a minimum age of 780 ka for the human-bearing sedimentary layer. A change in magnetic polarity, from reverse to normal (up section), was detected in the uppermost part of the TD7 stratigraphic layer, which overlies the fossiliferous level TD6. This geomagnetic reversal is interpreted as the Matuyama-Brunhes boundary

(780 ka), as suggested by biostratigraphy (Cuenca-Bescós and García, 2007; Cuenca-Bescos et al., 2010) and combined U-series/ESR analyses (Falguères et al., 1999; Parés et al., 2013). The latter was performed on three teeth from TD8, about 1.5 m above the Aurora Stratum, and yielded a mean age of 0.60 ± 0.05 Ma (Falguères et al., 1999). More recently, Arnold and Demuro (2015) reported a TT-OSL age of 851 ± 46 ka for horizon TD6-3 (Figure 3).

Summary

Paleomagnetism, including magnetostratigraphy and archaeomagnetism, is a useful tool for geoarchaeologists and is habitually the first method chosen for age dating in very early periods. It gives data on remanent magnetization recorded in rocks, sediments, and artifacts, which may help in establishing chronologies by age equivalence. If polarity zones of a magnetic stratigraphy profile can be unambiguously correlated to the GPTS, they provide a precise temporal framework for sedimentary sequences.

Bibliography

Arnold, L., and Demuro, M., 2015. Insights into TT-OSL signal stability from single-grain analyses of known-age deposits at Atapuerca, Spain. Quaternary Geochronology, 30, 472–478, doi:10.1016/j.quageo.2015.02.005.

As, J. A., and Zijderveld, J. D. A., 1958. Magnetic cleaning of rocks in paleomagnetic research. *Geophysical Journal of the Royal Astronomical Society*, **1**, 308–319.

Berger, G. W., Pérez-González, A., Carbonell, E., Arsuaga, J. L., Bermúdez de Castro, J. M., and Ku, T.-L., 2008. Luminescence chronology of cave sediments at the Atapuerca paleoanthropological site, Spain. *Journal of Human Evolution*, **55**(2), 300–311.

Bermúdez de Castro, J. M., Pérez-González, A., Martinón-Torres, M., Gómez-Robles, A., Rosell, J., Prado, L., Sarmiento, S., and Carbonell, E., 2008. A new early Pleistocene hominin mandible from Atapuerca-TD6, Spain. *Journal of Human Evolution*, **55**(4), 729–735.

Butler, R. F., 1992. *Paleomagnetism: Magnetic Domains to Geologic Terranes*. Boston: Blackwell Scientific Publications.

Cande, S. C., and Kent, D. V., 1995. Revised calibration of the geomagnetic polarity timescale for the Late Cretaceous and Cenozoic. *Journal of Geophysical Research, Solid Earth*, **100** (B3), 6095–6095.

Channell, J. E. T., Mazaud, A., Sullivan, P., Turner, S., and Raymo, M. E., 2002. Geomagnetic excursions and paleointensities in the Matuyama Chron at Ocean Drilling Program Sites 983 and 984 (Iceland Basin). *Journal of Geophysical Research, Solid Earth*, **107**(B6), 2114, doi:10.1029/2001JB000491.

Channell, J. E. T., Xuan, C., and Hodell, D. A., 2009. Stacking paleointensity and oxygen isotope data for the last 1.5 Myr (PISO-1500). *Earth and Planetary Science Letters*, **283**(1–4), 14–23.

Channell, J. E. T., Hodell, D. A., and Curtis, J. H., 2012. ODP Site 1063 (Bermuda Rise) revisited: oxygen isotopes, excursions and paleointensity in the Brunhes Chron. *Geochemistry, Geophysics, Geosystems*, **13**(1), Q02001, doi:10.1029/2011GC003897.

Cuenca-Bescós, G., and García, N., 2007. Biostratigraphic succession of the Early and Middle Pleistocene mammal faunas of the Atapuerca cave sites (Burgos, Spain). *Courier Forschungsinstitut Senckenberg*, **259**, 99–110.

Cuenca-Bescós, G., Rofes, J., López-García, J. M., Blain, H.-A., De Marfá, R. J., Galindo-Pellicena, M. A., Bennásar-Serra, M. L., Melero-Rubio, M., Arsuaga, J. L., Bermúdez de Castro, J. M., and Carbonell, E., 2010. Biochronology of Spanish quaternary small vertebrate faunas. *Quaternary International*, **212**(2), 109–119.

Eighmy, J. L., and Sternberg, R. S., 1990. *Archaeomagnetic Dating*. Tucson: University of Arizona Press.

Falguères, C., Bahain, J.-J., Yokoyama, Y., Arsuaga, J. L., Bermúdez de Castro, J. M., Carbonell, E., Bischoff, J. L., and Dolo, J.-M., 1999. Earliest humans in Europe: the age of TD6 Gran Dolina, Atapuerca, Spain. *Journal of Human Evolution*, **37**(3–4), 343–352.

Guyodo, Y., and Valet, J.-P., 1999. Integration of volcanic and sedimentary records of paleointensity: constraints imposed by irregular eruption rates. *Geophysical Research Letters*, **26**(24), 3669–3672.

Hagstrum, J. T., and Blinman, E., 2010. Archeomagnetic dating in western North America: an updated reference curve based on paleomagnetic and archeomagnetic data sets. *Geochemistry, Geophysics, Geosystems*, **11**(6), Q06009, doi:10.1029/2009GC002979.

Kovacheva, M., Boyadziev, Y., Kostadinova-Avramova, M., Jordanova, N., and Donadini, F., 2009. Updated archeomagnetic data set of the past 8 millennia from the Sofia laboratory, Bulgaria. *Geochemistry, Geophysics, Geosystems*, **10**(5), Q05002, doi:10.1029/2008GC002347.

Laj, C., and Channell, J. E. T., 2007. Geomagnetic excursions. In Kono, M. (ed.), *Treatise on Geophysics, volume 5: Geomagnetism*. Amsterdam: Elsevier, pp. 373–416.

Lanos, P., 2004. Bayesian inference of calibration curves: application to archaeomagnetism. In Buck, C. E., and Millard, A. (eds.), *Tools for Constructing Chronologies: Crossing Disciplinary Boundaries*. London: Springer. Lecture Notes in Statistics no. 177, pp. 43–82.

Lepre, C. J., and Kent, D. V., 2010. New magnetostratigraphy for the Olduvai Subchron in the Koobi Fora Formation, northwest Kenya, with implications for early Homo. *Earth and Planetary Science Letters*, **290**(3–4), 362–374.

Merrill, R. T., McElhinny, M. W., and McFadden, P. L. (eds.), 1996. *The Magnetic Field of the Earth: Paleomagnetism, the Core, and the Deep Mantle*. San Diego: Academic.

Oms, O., Parés, J. M., Martínez-Navarro, B., Agustí, J., Toro, I., Martínez-Fernández, G., and Turq, A., 2000. Early human occupation of Western Europe: paleomagnetic dates for two paleolithic sites in Spain. *Proceedings of the National Academy of Sciences*, **97**(19), 10666–10670.

Opdyke, N. D., and Channell, J. E. T., 1996. *Magnetic Stratigraphy*. San Diego: Academic.

Parés, J. M., Lee., A., Duval., M., Demuro, D., Pérez-González, A., Bermúdez de Castro, J. M., Carbonell, E., and Arsuaga, J. L., 2013. Reassessing the age of Atapuerca TD-6 (Spain): New paleomagnetic data. Journal of Archaeological Science, 40, 4586–4595, doi:10.1016/j.jas.2013.06.013.

Parés, J. M., and Pérez-González, A., 1995. Paleomagnetic age for hominid fossils at Atapuerca archaeological site, Spain. *Science*, **269**(5225), 830–832.

Parés, J. M., and Pérez-González, A., 1999. Magnetochronology and stratigraphy at Gran Dolina section, Atapuerca (Burgos, Spain). *Journal of Human Evolution*, **37**(3–4), 325–342.

Parés, J. M., Pérez-González, A., Rosas, A., Benito, A., Bermúdez de Castro, J. M., Carbonell, E., and Huguet, R., 2006. Matuyama-age lithic tools from the Sima del Elefante site, Atapuerca (northern Spain). *Journal of Human Evolution*, **50**(2), 163–169.

Parés, J. M., Pérez-González, A., Arsuaga, J. L., Bermúdez de Castro, J. M., Carbonell, E., and Ortega, A. I., 2010. Characterizing the sedimentary history of cave deposits, using archaeomagnetism and rock magnetism, Atapuerca (northern Spain). *Archaeometry*, **52**(5), 882–898.

Pavón-Carrasco, F. J., Osete, M. L., Torta, J. M., and Gaya-Piqué, L. R., 2009. A regional archeomagnetic model for Europe for the last 3000 years, SCHA.DIF.3K: applications to archeomagnetic dating. *Geochemistry, Geophysics, Geosystems*, **10**(3), Q03013, doi:10.1029/2008GC002244.
Pavón-Carrasco, F. J., Osete, M. L., and Torta, J. M., 2010. Regional modeling of the geomagnetic field in Europe from 6000 to 1000 B.C. *Geochemistry, Geophysics, Geosystems*, **11**(11), Q11008, doi:10.1029/2010GC003197.
Tamrat, E., Thouveny, N., and Taieb, M., 1996. Magnetostratigraphy of the lower member of the Hadar Formation (Ethiopia): evidence for a short normal event in the mammoth subchron. *Studia Geophysica et Geodaetica*, **40**(3), 313–335.
Tanguy, J.-C., Le Goff, M., Principe, C., Arrighi, S., Chillemi, V., Paiotti, A., La Delfa, S., and Patanè, G., 2003. Archaeomagnetic dating of Mediterranean volcanics of the last 2100 years: validity and limits. *Earth and Planetary Science Letters*, **211**(1–2), 111–124.
Tarling, D. H., 1971. *Principles and Applications of Palaeomagnetism*. London: Chapman and Hall.
Tauxe, L., 2010. *Essentials of Paleomagnetism*. Berkeley: University California Press.
Tauxe, L., and Kent, D. V., 1984. Properties of a detrital remanence carried by hematite from study of modern river deposits and laboratory redeposition experiments. *Geophysical Journal of the Royal Astronomical Society*, **76**, 543–561.
Thouveny, N., Carcaillet, J., Moreno, E., Leduc, G., and Nérini, D., 2004. Geomagnetic moment variation and paleomagnetic excursions since 400 kyr BP: a stacked record from sedimentary sequences of the Portuguese margin. *Earth and Planetary Science Letters*, **219**(3–4), 377–396.
Valet, J.-P., Meynadier, L., and Guyodo, Y., 2005. Geomagnetic dipole strength and reversal rate over the past two million years. *Nature*, **435**(7043), 802–805.
Verosub, K. L., Goren-Inbar, N., Feibel, C. S., and Saragusti, I., 1998. Location of the Matuyama/Brunhes boundary in the Gesher Benot Ya'aqov archaeological site. *Journal of Human Evolution*, **34**(3), A22.

Cross-references

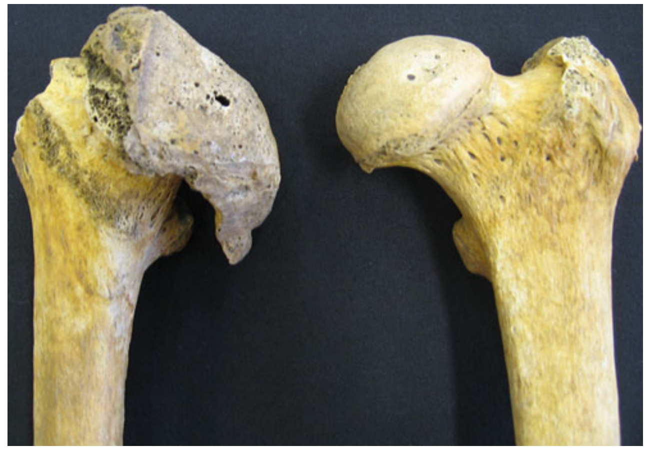
^{40}Ar/^{39}Ar and K–Ar Geochronology
Archaeomagnetic Dating
Atapuerca
Magnetometry for Archaeology
Susceptibility

PALEOPATHOLOGY

Charlotte A. Roberts
Department of Archaeology, Durham University, Durham, UK

Definition and history of study

Paleopathology is defined as the scientific study of the evidence of disease in human and non human remains from archaeological sites (Tombs) and was first described as such by Marc Armand Ruffer in the early twentieth century (Ruffer, 1910). Human remains are the primary source of evidence for past disease (Roberts and Manchester, 2005). Other forms of evidence are provided in historical documents and art (e.g., Rawcliffe, 2006 on leprosy in medieval England), but these data can prove difficult to interpret. Whilst evidence for disease in human remains can be challenging to diagnose and interpret, artists and authors may be biased in their representations of the range of diseases from which people suffered, and signs and symptoms illustrated and written about can often be very difficult to associate with specific diseases. Furthermore, it was often the more dramatic diseases that were considered, while the more commonplace ones were ignored. However, documentary and art evidence for disease can help to reveal those conditions that affected only the soft tissues such as those common in childhood.



Paleopathology, Figure 1 Normal femur head on the *right* and diseased head of femur on the *left* side of the picture (diseased femur head is abnormally flattened and has signs of osteoarthritis: new bone formation on the underside of the head and "holes" in the head).

Paleopathology is a subdiscipline of physical anthropology (the study of humans from past to present – Jurmain et al., 2008) and bioarchaeology (the study of human remains within their archaeological context – Buikstra and Beck, 2006). Most people working in the field are those with an archaeological or anthropological training, although there are important and invaluable contributions from medical doctors, anatomists, and dentists. To be able to work within the discipline, it is necessary to have an excellent familiarity with the normal appearance of the skeleton and its associated soft tissues in order to be able to recognize the abnormal diseased state (Figure 1); this is in addition to being able to identify often fragmentary and poorly preserved human remains, including those that have been cremated, and distinguish between human and non human bones and teeth (Figure 2).

Most of the time, the remains studied are skeletons because those are the most common remains to be excavated (Figure 3), but in areas of the world where there are specific environmental conditions, whole bodies may be excavated, thus providing potential evidence of disease

Paleopathology, Figure 2 Horse femur on the *left* and human femur on the *right side* (the bones have similar features but the proportions and size of features differ).

Paleopathology, Figure 3 7th-8th century AD skeleton buried at the Bowl Hole cemetery, Bamburgh Castle, Northumberland, England (Courtesy of Sarah Groves and Graeme Young).

affecting the soft tissues of the body (Aufderheide, 2000; Lynnerup, 2007). Paleopathology has had a long history stretching back into the seventeenth century in Switzerland (Buikstra and Roberts, 2012), which initially was concentrated on archaeological animal remains (e.g., see Figure 4, and more recent work in Davies et al., 2005), later being transferred to those of humans. Most early work on human remains considered individual skeletons or mummies (Ruffer, 1913), often without considering the remains within their cultural context, and it was not until around the early twentieth century that larger groups of skeletons were studied, thus providing a population-based approach to understanding health (Aufderheide and Rodríguez-Martín, 1998). However, this approach did not become common until much later, and in some parts of the world even today, "case studies" are the norm for reporting disease in the past.

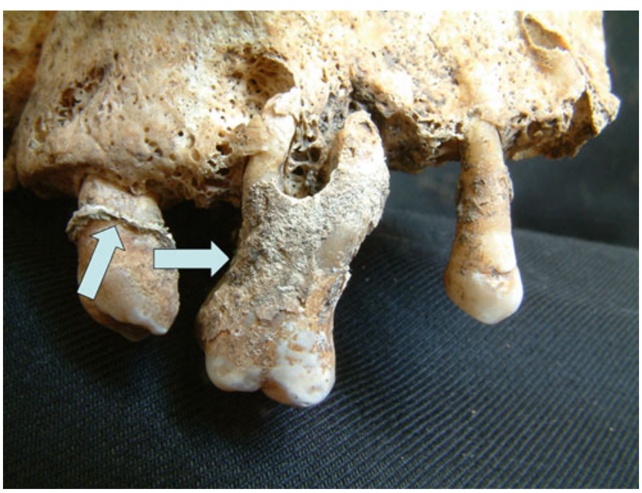
Methods of study

Paleopathology is studied by observing abnormal alterations to the body tissues as evidenced in human remains excavated from archaeological sites. While soft tissues can be studied when they are preserved, a focus here is taken on observations of skeletal remains (bones and teeth). The two key bone changes that can represent disease are bone formation and bone destruction or a combination of the two (Figure 5). In the teeth, disease is represented by loss of dental tissue such as enamel and addition of plaque or tartar in the form of calculus (Figure 6); the bones of the jaws can also be involved, for example, when an abscess affects the person (Figure 7). Bone formation may appear as active woven bone (porous and additional to the original bone cortex) or as healed lamellar bone (chronic and incorporated into the original cortex, indicating healing). Likewise, destruction of bone may be active (unhealed edges to lesions) or healed (edges are rounded). If lesions indicate "activity" then the disease process is deemed active at the time of death. In the case of teeth, destruction of dental tissue is permanent and does not heal. Standard methods have been developed that scholars are encouraged to use (Buikstra and Ubelaker, 1994; Grauer, 2008), and there are many texts that provide useful data for diagnosis and interpretation (Ortner, 2003).

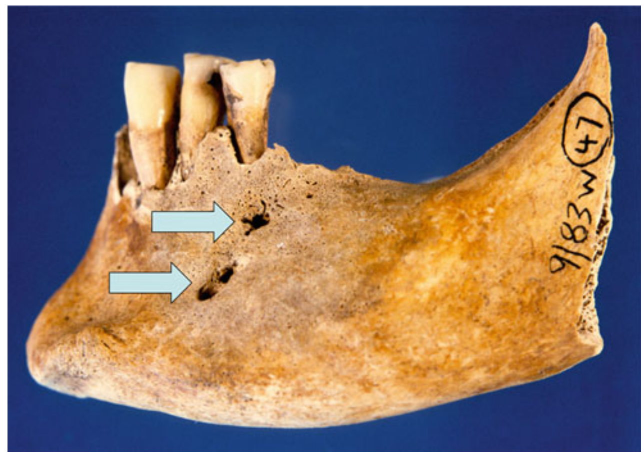
The initial recording of the remains to identify pathological lesions is done by making comparisons between the bones and teeth being observed and normal bones and teeth so that the abnormalities can be recognized. However, there are abnormalities of the bones and teeth that are considered normal variants and are not

Paleopathology, Figure 4 Diseased bone of a sheep on the *left side* compared to a normal one on the *left* (Courtesy of Julie Bond).

Paleopathology, Figure 5 Bone formation and bone destruction on ribs, late Medieval Ireland (Courtesy of Eileen Murphy); *arrows* show examples of the bone destruction (blue) and formation (red).



Paleopathology, Figure 6 Dental calculus (plaque) on teeth, nineteenth century England (Courtesy of Anwen Caffell); *arrows* show the deposits of calculus.



Paleopathology, Figure 7 Dental abscess affecting a lower jawbone, fourth century AD England; *arrows* show the holes (bone destruction) of the abscess where pus drained out into the soft tissues of the jaw.

Paleopathology, Figure 8 Cervical (neck) vertebrae: normal on *right* (one hole) and abnormal on *left* (two holes).

pathologically induced. These are termed non metric traits, some of which can be inherited through families (Tyrrell, 2000; Scott, 2008) – Figure 8. Once the pathological lesions have been noted, making sure that postmortem damage is not mistaken for a disease process, and using detailed descriptions, their distribution pattern is then recorded. This is important for considering possible (differential) diagnoses. It is only possible for the skeleton to react in a limited number of ways to the impact of disease, and therefore similar bone changes can occur in different bone diseases. For example, there are many different diseases that affect the joints, but different joints can be affected in different diseases. It is therefore important to consider all diseases that could have created the bone changes. Similarly, it is vital that the distribution patterns of lesions are examined because, in archaeological contexts skeletons can be fragmentary, and it is often not possible to be certain of a specific disease diagnosis. The distribution pattern of lesions is then compared with what is known in the clinical medical record about how diseases affect the skeleton; this does however assume that reactions to disease in the skeleton have not changed over time. Diagnosis is challenging as there are limited methods available (Waldron, 1994). Diseases that may be recognized in skeletal remains are those affecting the teeth (e.g., caries), joints (e.g., osteoarthritis), the endocrine glands (e.g., hypothyroidism), and metabolism (e.g., scurvy), along with infections (e.g., tuberculosis), congenital conditions (e.g., spina bifida) and tumors, not forgetting the effects of accidents and interpersonal violence in the form of traumatic lesions such as fractures.

Once the pathological data have been collected from the skeletons or mummies, they are analyzed to produce frequency rates for diseases observed according to age and sex (Paleodemography), although this will underestimate the absolute frequency of disease (see below for Limitations). It may also be possible to look at disease in relation to status if the burial record provides evidence of different statuses, for example, in grave good inclusions (Jankauskas, 1999). Following on from analysis of the data, the frequency of disease is then interpreted with reference to what is known about the lives of the people under study. For example, if dental diseases are noted, the diet (Paleodiet) needs to be known because a diet high in carbohydrates would, for example, lead to dental caries. Knowledge of what diet people were eating may be gained from evidence of plant and animal remains at an associated contemporary settlement site along with evidence for economic practices (e.g., agriculture) and food-processing artifacts such as querns used to grind grain (Figure 9). Additionally, stable isotope analyses of carbon and nitrogen levels in bone provide an indication of the general type of diet eaten (Muldner and Richards, 2007). This is termed the "bioarchaeological" or "biocultural" approach; disease data should always be interpreted with reference to the context of the remains studied.

Most scholars record the evidence visually, sometimes with low-power magnification (magnifying glass or binocular microscope). However, radiography, a non destructive analytical method, has also been used regularly to aid diagnosis because the internal structure of bones can be altered by disease (Mays et al., 2006) – Figure 10. Without radiography, these changes would not be visible (Grauer and Roberts, 1996). Routine "plain film" radiographs are the norm, but in recent years, more sophisticated imaging methods have been applied.

Paleopathology, Figure 9 Quernstone, and shells indicating seafood was eaten, at the multiperiod site of Jarlshof, Shetland Islands, Scotland (Bronze Age to the 16th century AD).

Paleopathology, Figure 10 Radiograph showing healed fracture of a fibula, early Medieval England (arrow shows fracture line).

These have included computed tomography (CT) and micro-CT, where "slices" of bones and teeth can be viewed; this has proved particularly valuable for mummified remains (Pernter et al., 2007 – Oetzi). Paleopathologists have also used destructive techniques to diagnose disease, and these have included histological analysis (Schultz, 2001) and more recently biomolecular analysis (Brown and Brown, 2011). The latter has particularly enabled diagnoses of diseases that only affect the skeleton, for example, malaria (Taylor et al., 1997), but the method is still developing along side with methods in biomolecular science.

Limitations of study

Paleopathology is not without challenges, succinctly stated by Wood et al. (1992). It should be remembered that the preservation of a skeleton or a mummy will affect the survival, observation and recording of pathological lesions, so poorly preserved remains will reveal less evidence, and it will be harder to make more specific diagnoses. There is also an assumption that how diseases affect the skeleton has not changed over thousands of years. The focus is on using clinical data on skeletal changes due to disease in people who have not had access to any treatment, for example before antibiotics were used for infections. It should therefore be emphasized that in more recent times, the way in which a disease affects the skeleton could have changed if a person had treatments such as drug therapy, and it is much more likely that treatment would ultimately prevent progression of the disease into the skeleton anyway. This has implications for using disease (along with a suite of other characteristics) as a way of identifying victims of crime in forensic anthropology (Thompson and Black, 2006).

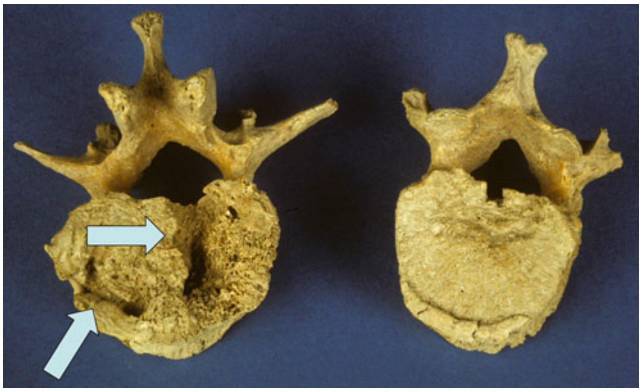
As discussed above, when dealing with skeletons, it is only the diseases that can potentially affect bones and teeth that are identified, although, despite debates about authenticity, ancient DNA analysis of pathogens such as bacteria that cause infections are now being done, but not without controversy (Raoult et al., 2000; Gilbert et al., 2004). Another problem is that for many diseases, only a few percent of (untreated) people will be affected; for example, the infectious disease of leprosy will only affect the skeleton in 3–5 % of people, dependent on their immune response to the bacteria. A person with a high resistance to the bacteria may not develop bone changes, but one who has not. Most evidence is chronic in nature and is interpreted as representing a "healthy" person, with that evidence considered a sign that the person survived the acute stages of the disease. Those without any bone changes of course died of some disease or injury, but it may have killed them quickly, leaving no chance for the disease to make its mark on the skeleton (or the cause of death was a soft tissue disease). When producing frequency rates for disease, those rates will not represent reality for many reasons, including the preceding problems, but also because it is usually not known how representative the dead are of the living population being analyzed. Furthermore, it is not usually possible to detect increases and decreases in disease in cemetery populations because it is usually impossible to divide the skeletons of any one cemetery into smaller time ranges beyond a time range of several hundred years for the whole cemetery's lifespan (see Waldron, 1994).

"Case studies" versus "population" studies in paleopathology

Early on in its history, paleopathology was focused on "case studies" documenting diseases in individual skeletons or mummies at a specific place and time. Often, these studies were devoid of context, commonly reflecting lack of archaeological or anthropological training for those working in the field. While these studies continue to be useful to the discipline, there has been increasing emphasis over the years on population-based work (e.g., see Mays, 2010, 2012). Scholars now regularly focus their studies on testing a generated hypothesis and using specific questions to direct their studies, on the basis of their collected and analyzed data, the hypothesis proposed will be supported or rejected. For example, a number of studies have hypothesized that urban living created more health problems in the medieval period, a hypothesis often upheld. For example, Roberts (2007) discusses facial sinus inflammation in relation to poor air quality, especially in urban Medieval Europe. However, there can be exceptions to poor health in urban environments (e.g., see Judd and Roberts, 1999 where rural medieval people had more fractures than urban people).

Knowledge gained and benefits to archaeology and society today

Over its long history, paleopathology has contributed much to our understanding of the health challenges people faced in the past. The data in general suggest that health has declined as time has gone by and societies have become more complex in how they live, eat and work (e.g., see Steckel and Rose, 2002 on the Americas; Roberts and Cox, 2003 on Britain; Cohen and Crane-Kramer, 2007 for a global view). There are, of course, exceptions, but this seems to be the general trend; living as a hunter–gatherer was healthier than being in a permanent settlement where agriculture was practiced, or living in an urban or industrialized setting. Of course, this is based on studying skeletal remains, and therefore, the broad range of health problems people experienced in the past cannot be seen. This overall view of a decline in health has been developed not only by synthetic work but also through studies of human remains from individual archaeological sites throughout the world, although the amount of study varies depending on availability of training and the absolute number of scholars working in those areas. For example, the USA. and Europe have produced more data than some parts of the world, but times are changing. There are also more focused studies on specific diseases that have informed us about when and where diseases originated and how they have developed over time (e.g., see Roberts and Buikstra, 2003; Powell and Cook, 2005). For example, the earliest evidence for the bacterial infection tuberculosis comes from a number of European



Paleopathology, Figure 11 Destructive lesions (*arrows*) in a vertebra, probably tuberculosis, early Medieval England.

countries and is several thousands years old, but the disease did not become common until Medieval urban living impacted the lives of those people (Figure 11). Paleopathology in more recent times has developed considerably and is now producing data using more sophisticated methods of analysis (e.g., pathogen aDNA analysis and imaging techniques, see above) than has ever been possible before.

How does this work help archaeology and indeed society today? For archaeology as a discipline, one has to remember that without humans, there would be no archaeological evidence. People built settlements and burial monuments, domesticated animals and plants, and made pottery and other artifacts. Knowledge about their health therefore is imperative to understand the past and how society functioned. If a large proportion of people in a population was sick (as we might see today), life could not proceed as normal, and ultimately the socio-economic basis for survival could be threatened, as seen in the Medieval Black Death that killed a large part of Europe's population (Park, 1993). As for society today, paleopathology provides the time depth to the history of disease that allows us to visualize the peaks and troughs in diseases over thousands of years, something that is simply not possible to do when studying disease in the living. It allows us to consider what factors were important for disease to flourish and decline. Intrinsic (age at death, sex, ethnicity) and extrinsic (e.g., diet, living conditions, hygiene levels, occupation) factors create situations where diseases may take advantage and establish and maintain themselves. Paleopathology provides some indication of how to plan for the future, and scholars in the discipline are starting much more to focus on contemporary health problems. Paleopathology is also contributing to the newly emerging discipline of evolutionary medicine (e.g., see Nesse and Williams, 1994) "Evolutionary ways of thinking and doing research may lead to new ways of treating and preventing diseases and disorders, potentially saving lives, or at the very least, improving the quality of life for those whose conditions compromise health or lead to early death" (Trevathan et al., 2008, p. 10).

Future developments

There are an ever-increasing number of scholars working in paleopathology, even in remoter parts of the world that until recently had produced little data on the history of disease in human remains; this is undoubtedly because training has become more widespread, people from other countries are working on human remains in those places, or scholars are being trained elsewhere and returning home to work on human remains with newly developed skills. Countries seeing this trend emerge will naturally be slower in producing the much needed population-based studies in paleopathology more common in the United States and Europe, but in time these will come. Without a doubt, as methods develop, there will be increasingly more attention paid to using biomolecular analysis to diagnose disease in human remains (e.g., see Bouwman et al. 2012), notwithstanding some of the limitations identified (e.g., see Roberts and Ingham, 2008; Wilbur et al., 2009). Paleopathology has a promising future in helping the world plan for the health of its population.

Summary

Paleopathology is the study of ancient disease seen in animal and human remains excavated from archaeological sites. It has had a long history of study and helps us to understand how disease has shaped human populations today. It is based in clinical medicine, practiced mainly by people with archaeological and anthropological backgrounds, and it emphasizes contextualization of data collected to understand patterns seen. It provides a deep time perspective on health, contributes to evolutionary medicine and utilizes a range of methods of analysis.

Bibliography

Aufderheide, A., 2000. *Scientific Study of Mummies*. Cambridge, UK: Cambridge University Press.

Aufderheide, A., and Rodríguez-Martín, C., 1998. *The Cambridge Encyclopedia of Human Palaeopathology*. Cambridge, UK: Cambridge University Press.

Bouwman, A. S., Kennedy, S. L., Müller, R., Stephens, R. H., Holst, M., Caffell, A. C., Robert, C. A., and Brown, T. A., 2012. The genotype of a historic strain of *Mycobacterium tuberculosis*. *Proceedings of the National Academy of Sciences USA*, **109**(45), 18511–18516.

Brown, T., and Brown, K., 2011. *Biomolecular Archaeology. An Introduction*. Chichester: Wiley-Blackwell.

Buikstra, J. E., and Beck, L. A. (eds.), 2006. *Bioarchaeology. The Contextual Analysis of Human Remains*. Oxford: Elsevier.

Buikstra, J. E., and Roberts, C. A. (eds.), 2012. *The Global History of Paleopathology: Pioneers and Prospects*. New York: Oxford University Press.

Buikstra, J. E., and Ubelaker, D. (eds.), 1994. *Standards for Data Collection from Human Skeletal Remains*. Fayetteville, Arkansas, U.S.A.: Archaeological Survey Research Seminar Series 44.

Cohen, M. N., and Crane-Kramer, G. (eds.), 2007. *Ancient Health. Skeletal Indicators of Agricultural and Economic Intensification*. Gainesville, FL: University Press of Florida.
Davies, J., Fabiš, M., Mainland, I., Richards, M., and Thomas, R. (eds.), 2005. *Diet and Health in Past Animal Populations: Current Research and Future Directions*. Oxford: Oxbow Books.
Gilbert, M. T. P., Cuccui, J., White, W., Lynnerup, N., Titball, R. W., Cooper, A., and Prentice, M. B., 2004. Absence of *Yersinia pestis*-specific DNA in human teeth from five European excavations of putative plague victims. *Microbiology*, **150**, 341–354.
Grauer, A., 2008. Macroscopic analysis and data collection in palaeopathology. In Pinhasi, R., and Mays, S. (eds.), *Advances in Palaeopathology*. Chichester: Wiley, pp. 57–76.
Grauer, A., and Roberts, C. A., 1996. Palaeoepidemiology, healing and possible treatment of trauma in the medieval cemetery population of St Helen-on-the-Walls, York, England. *American Journal of Physical Anthropology*, **100**, 531–544.
Jankauskas, R., 1999. The incidence of diffuse idiopathic skeletal hyperostosis and social status correlations. *International Journal of Osteoarchaeology*, **13**, 289–293.
Judd, M., and Roberts, C. A., 1999. Fracture trauma in a Medieval farming village. *American Journal of Physical Anthropology*, **109**, 229–243.
Jurmain, R., Kilgore, L., Trevathan, W., and Nelson, H. (eds.), 2008. *Introduction to Physical Anthropology*, 11th edn. Belmont, CA: Wadsworth.
Lynnerup, N., 2007. Mummies. *Yearbook of Physical Anthropology*, **50**, 162–190.
Mays, S., 2010. Human osteoarchaeology in the UK 2001–2007: a bibliometric perspective. *International Journal of Osteoarchaeology*, **20**, 192–204.
Mays, S., 2012. The impact of case reports relative to other types of publication in palaeopathology. *International Journal of Osteoarchaeology* **22**, 81–85.
Mays, S., Brickley, M., and Ives, R., 2006. Skeletal manifestations of rickets in infants and young children in a historic population from England. *American Journal of Physical Anthropology*, **129**, 362–374.
Müldner, G., and Richards, M. P., 2007. Diet and diversity at later medieval Fishergate: the isotopic evidence. *American Journal of Physical Anthropology*, **134**, 162–174.
Nesse, R. M., and Williams, G. C., 1994. *Why We Get Sick – The New Science of Darwinian Medicine*. New York: Times Books.
Ortner, D. J., 2003. *Identification of Pathological Conditions in Human Skeletal Remains*. London: Academic.
Park, K., 1993. Black death. In Kiple, K. (ed.), *The Cambridge World History of Human Disease*. Cambridge: Cambridge University Press, pp. 612–616.
Pernter, P., Gostner, P., Vigl, E. E., and Ruhli, F. J., 2007. Radiological proof for the cause of the Iceman's cause of death (ca 5300 BP). *Journal of Archaeological Science*, **34**, 1784–1786.
Powell, M. L., and Cook, D. C. (eds.), 2005. *The Myth of Syphilis: The Natural History of Treponematosis in North America*. Gainesville, FL: University Press of Florida.
Raoult, D., Aboudharam, G., Crubezy, E., Larrouy, G., Ludes, B., and Drancourt, M., 2000. Molecular identification of 'suicide' PCR of *Yersinia pestis* as the agent of medieval black death. *Proceedings of the National Academy of Sciences USA*, **97**, 12800–12803.
Rawcliffe, C., 2006. *Leprosy in Medieval England*. Woodbridge: Boydell Press.
Roberts, C. A., 2007. A bioarchaeological study of maxillary sinusitis. *American Journal of Physical Anthropology*, **133**, 792–807.
Roberts, C. A., and Buikstra, J. E., 2003. *The Bioarchaeology of Tuberculosis: A Global View on a Remerging Disease*. Gainesville, FL: University Press of Florida.
Roberts, C. A., and Cox, M., 2003. *Health and Disease in Britain: From Prehistory to the Present Day*. Stroud: Sutton Publishing.
Roberts, C. A., and Ingham, S., 2008. Using ancient DNA analysis in palaeopathology: a critical analysis of published papers with recommendations for future work. *International Journal of Osteoarchaeology*, **18**, 600–613.
Roberts, C. A., and Manchester, K., 2005. *The Archaeology of Disease*. Stroud, UK: Sutton Publishing.
Ruffer, M. A., 1910. Remarks on the histology and pathological anatomy of Egyptian mummies. *Cairo Scientific Journal*, **4**, 1–5.
Ruffer, M. A., 1913. On pathological lesions in Coptic bodies. *Journal of Pathology and Bacteriology*, **18**, 149–162.
Schultz, M., 2001. Paleohistology of bone: a new approach to the study of ancient diseases. *Yearbook of Physical Anthropology*, **44**, 106–147.
Scott, G. R., 2008. Dental morphology. In Katzenberg, M. A., and Saunders, S. R. (eds.), *Biological Anthropology of the Human Skeleton*. Chichester: Wiley-Liss, pp. 265–298.
Steckel, R., and Rose, J. C. (eds.), 2002. *The Backbone of History: Health and Nutrition in the Western Hemisphere*. Cambridge: Cambridge University Press.
Taylor, G. M., Rutland, R., and Molleson, T., 1997. A sensitive polymerase chain reaction method for the detection of P*lasmodium* species DNA in ancient human remains. *Ancient Biomolecules*, **1**, 193–203.
Thompson, T., and Black, S. (eds.), 2006. *Forensic Human Identification: An Introduction*. London: CRC Press.
Trevathan, W. R., Smith, E. O., and McKenna, J. J. (eds.), 2008. *Evolutionary Medicine and Health. New Perspectives*. New York: Oxford University Press.
Tyrrell, A., 2000. Skeletal non-metric traits and the assessment of intra- and inter-population diversity: past problems and future potential. In Cox, M., and Mays, S. (eds.), *Human Osteology in Archaeology and Forensic Science*. London: Greenwich Medical Media, pp. 289–236.
Waldron, T., 1994. *Counting the Dead. The Epidemiology of Skeletal Populations*. Chichester: Wiley.
Wilbur, A. K., Stone, A. C., Roberts, C. A., Pfister, L., Buikstra, J. E., and Brown, T. A., 2009. Deficiencies and challenges in the study of ancient tuberculosis DNA. *Journal of Archaeological Science*, **36**, 1990–1997.
Wood, J. W., Milner, G. R., Harpending, H. C., and Weiss, K. M., 1992. The osteological paradox. Problems of inferring health from skeletal samples. *Current Anthropology*, **33**, 343–370.

Cross-references

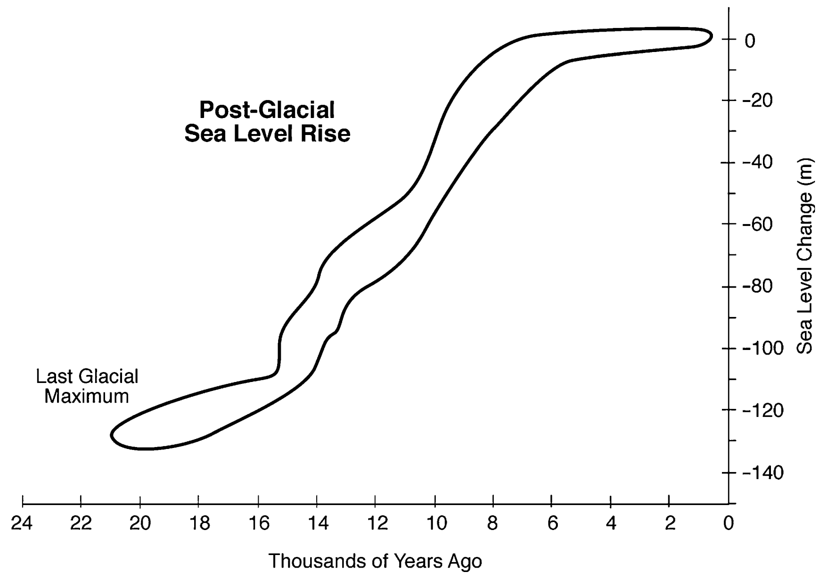
Tombs

PALEOSHORES (LAKES AND SEA)

Christophe Morhange[1], Michel Magny[2] and Nick Marriner[3]
[1]CNRS CEREGE, UMR 6635, Aix-Marseille University, Aix-en-Provence, France
[2]CNRS, UMR 6249, CNRS, Laboratoire Chrono-Environnement, Besançon, France
[3]CNRS, Laboratoire Chrono-Environnement UMR 6249 Université de Franche-Comté, Besançon, France

Introduction: traces on the Rhodian shore?

In his seminal book looking at nature and culture in western thinking, Glacken (1967) stated that geography, particularly geoarchaeology, poses the question of possibilism, the idea that the environment sets certain constraints and



Paleoshores (Lakes and Sea), Figure 1 Sea-level changes since 18,000 years BP (Adapted from Fleming et al., 1998). The outlined area subsumes the variability in sea level spatially and temporally (tides, oceanic circulation, etc.).

that humans can act as geomorphic agents. In this sense, shorelines are an archetypal interface to look at rapidly changing terrestrial and aquatic environments.

More than a century ago, the American geomorphologist John Wesley Powell introduced the term "base level" to define the elevation below which a stream cannot downcut deeper into its valley. Fluvial processes cease where a river flows into a large lake or the ocean because the hydraulic gradient is reduced to zero at the origin of sedimentary deposition (Chorley et al., 1964). Since the time of Powell's pioneering work, the ocean has been regarded as a reference base level even though sea level varies in space and time, and it is paramount in driving shoreline changes and human settlement geographies. One of the key advantages of living in coastal areas is access to marine resources, including mollusks, mammals, and birds, all of which provide potentially rich sources of energy and protein.

Geological evidence for relative sea-level changes and local crustal movements is critical to understanding the archaeological record in coastal areas. Gaps in the record increasingly point to the need for underwater exploration of submerged shorelines, and a growing body of evidence shows that archaeological sites are prevalent in submerged landscapes. Two major forcing factors explain shoreline deformations: (1) relative sea-level (RSL) changes and (2) modifications in sedimentary budgets at various spatiotemporal scales.

Geoarchaeology of paleoshorelines and Quaternary RSL changes

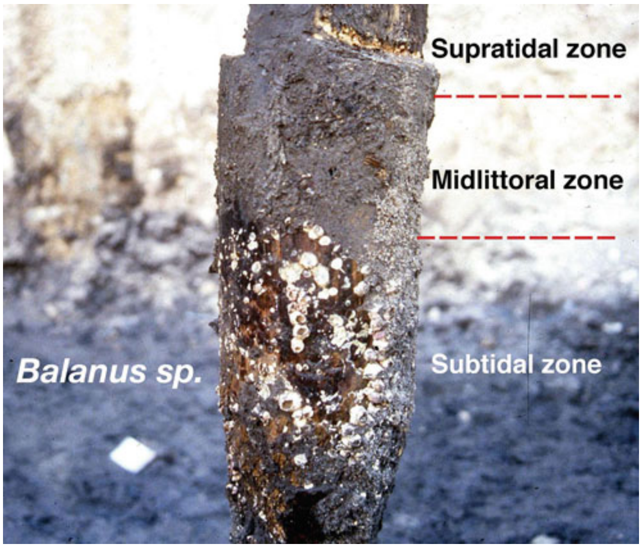
Past sea-level changes have been driven by eustatic and crustal factors, e.g., isostasy, tectonics, geoidal changes, and the effects of changes in the Earth's rotation. Over the past 20,000 years, these forcing agents have interacted at various spatial and temporal scales (references and synthesis in Church et al., 2010).

During the interval prior to ca. 6000 years BP, most sea-level curves are characterized by a general rise in the water level corresponding to the eustatic signature of melting continental-based ice caps. Once the last of the large ice caps had melted (around 6000 years BP), glacio-eustatism ended (e.g., Pirazzoli, 1991; Mörner, 1996; Lambeck and Bard, 2000) (Figure 1). Since this date, relative sea-level records have been dominated by crustal mobility and the irregular redistribution of water masses over the globe, primarily driven by variations in ocean and atmospheric circulation systems (marine currents, evaporation/precipitation budgets). Since the Neolithic, a plethora of archaeological indicators can be used to estimate RSL changes.

Archaeological and biological markers of RSL changes

Since 6000 years BP, ancient societies have left different types of coastal evidence indicating RSL changes, including town structures, anchorages, and ports. Submerged artifacts can provide interesting details to reconstruct ancient shoreline changes. The use of archaeological RSL markers draws upon the close interaction between archaeologists, geomorphologists, and biologists (Pirazzoli, 1976; Auriemma and Solinas, 2009).

Archaeological evidence for RSL variations is wide and varied (Flemming and Webb, 1986). Broadly speaking, it can be recovered within three zones.



Paleoshores (Lakes and Sea), Figure 2 Biological zoning on a wooden stake from the 1993 excavation of two sixth-century BC archaic Greek ships at the Place Jules-Verne site in Marseille (Morhange et al., 2001). Barnacles (*Balanus* sp.) mark the submerged infralittoral range on the piling, while the midlittoral and supralittoral sections are clearly discernible higher up.

1. The *supralittoral zone* includes residential units such as villae maritimae, private and public buildings, or town quarters (foundations, floors, roads, and pavements), thermal baths, plumbing installations (wells, aqueducts, cisterns, sewers, drains, gullies), tombs, and quarries. When inundated by rising seas, these remains can provide estimates for the amount of submersion.
2. The *midlittoral zone* includes interface structures such as quays, piers, breakwaters, or fishponds that exist at the sea level of the time. These constitute the most precise type of archaeological RSL indicators.
3. Finally, the *infralittoral zone* hosts structures such as wrecks or harbor foundations, which again provide broad estimates on the magnitude and direction of relative sea-level changes.

Under favorable conditions, measurements must be taken in relation to the mean biological sea level (MBSL), as defined by Laborel and Laborel-Deguen (1994). Marine biologists have demonstrated that, on hard substrates, the limit between the midlittoral and infralittoral zones is marked by a well-defined qualitative and quantitative change in the composition of benthic algal and animal populations (Figure 2). These subfossil zones can be preserved in the case of coastal uplift or silting of the archaeological site (Pirazzoli, 1977; Morhange et al., 2001). This limit also corresponds to distinct morphological features such as the vertex of tidal notches or the floor of erosion platforms (Pirazzoli, 1986). Seasonal or aperiodic sea-level changes have little or no influence on these biological and geomorphological belts.

Archaeological evidence brings with it varying degrees of precision when used to indicate the former RSL, and therefore care must be taken to ensure the indicator chosen has a reliable maritime association. It is also important to evaluate critically the functional elements of the indicator and the dimensions of the emerged part (if it has risen above the water) relative to present sea level (Auriemma and Solinas, 2009). Consequently, it is important to determine the chronology and the dynamics of its abandonment or destruction. This is achieved by archaeological surveys, sampling of the chronological indicators (ceramics, etc.), and excavation. Interdisciplinary work, drawing on archaeology, the geosciences, and marine biology, aims to (1) measure RSL variations based on the best preserved archaeological remains, (2) evaluate the height and functional depth of the indicator relative to mean sea level and if possible the MBSL, and (3) establish chronological and altitudinal error bars with relation to MBSL.

Geoarchaeological case studies of eustatic sea-level changes and recent RSL variations

Quaternary marine oscillations: the prehistory of land bridges and coastal resources

It is now well established that large sea-level fluctuations accompanied the glacial-interglacial cycle. The maximum amplitude of eustatic variation in response to continental glaciation was approximately 120 m, with relatively short periods of highstand punctuating much longer periods of lowstand. The pattern of sea-level change is best attested for the last glacial-interglacial cycle, but earlier cycles were accompanied by similar fluctuations back to 2.5 Ma (Lambeck et al., 2002).

The archaeological implications of these sea-level changes have been recognized for a long time. They significantly influence the visibility of marine resources at different periods, the preservation of coastal archaeological sites, human dispersal (the creation and submergence of land bridges), changes in shoreline ecology, and alterations in the paleo-economic potential of coastlines (Masters and Flemming, 1983; Bailey and Flemming, 2008). For example, prehistoric peoples were able to exploit exposed coastal and continental resources during sea-level lowstands, and crossings by land routes were facilitated by marine regressions; the Bering Strait lays above sea level and acted as a land bridge for human migration and the movement of other biota in the late Pleistocene until 11,000 years BP (Elias et al., 1996).

As Bailey (2004) stresses, the received wisdom of world prehistory has been dominated by land-based narratives, where hunter-gathering societies gradually adopted agriculture and domestication. Little emphasis has been placed on the use of coastlines and marine resources due to three consistent biases: (1) sea-level changes have removed evidence through erosion or submergence, (2) research biases have traditionally neglected coastal hunters and gatherers, and (3) a focus on technological "primitivism" in which the tools and knowledge to exploit coastal resources were a late development in human cultural development (Bailey, 2004). Nevertheless, coastal habitats are among the most attractive for human settlement, and they have played key roles as gateways to human movement and the rise of civilizations (Flemming, 2004).

Postglacial marine transgression and the prehistory of continental shelves

Popular interest in marine archaeology, combined with the democratization of scuba equipment, has resulted in remarkable offshore discoveries (Masters and Flemming, 1983). Recent advances in bathymetric mapping and geophysics have shed fresh light on the dynamics of shoreline changes and human ecology in coastal areas.

Key problems relate to the preservation of submerged material, the sequence of burial, and taphonomy processes. What are the possibilities of coastal/marine prehistoric deposits surviving into the present, either in primary or reworked contexts? What processes are most favorable to the survival of prehistoric sites? Can the pre-transgressive landscapes be precisely reconstructed? Destruction is greatest for sites located in areas directly exposed to breaking waves. It is important, therefore, that sediments rapidly cover archaeological sites in order to ensure their long-term survival in the geologic record (Bailey and Flemming, 2008; Bailey et al., 2008).

Based on sea-level data and local geological and geoarchaeological records, Perissoratis and Conispoliatis (2003) have established that, during oxygen isotope stage 2 (21,500 years BP, sea level at −120 m), extensively exposed continental shelves existed in the northern and eastern Aegean Sea (Greece) and central parts of the Ionian Sea. Many islands formed larger complexes and were connected with the mainland. The peripheries of many gulfs were subaerially exposed, while freshwater lakes formed in their central parts. At 11,500 years BP (sea level at −60 m), the surface area of the exposed shelf was already greatly diminished, and the advancing sea overflowed into most of the gulfs; just a few islands retained land bridges to the mainland. Finally, from 8000 years BP and onward, the sea drowned the lowlands and gulfs, but subsequent sediment input by fluvial systems induced rapid coastal changes. Thus, many human settlements and ancient cities with maritime orientations during Hellenistic or later times are today located tens of kilometers inland.

At shorter time scales, historical relative sea-level rise has submerged numerous archaeological sites, such as the settlement of Atlit Yam (Israel). Galili et al. (1993) were able to reconstruct a precise sea-level curve based on archaeological and sedimentological evidence from submerged sites. This work has elucidated two main stages of sea-level rise: from 8900 to 7000 years BP (sea level rose from −35 to −7 m) and from 7000 to 4000 years BP (sea level rose from −7 m to its present position). The resulting rapid landscape changes, combined with the loss of vital terrestrial and underwater resources (i.e., agriculture, pasture, hunting, and fishing grounds), must have necessitated ongoing adaptations by the coastal communities. By contrast, no major RSL changes have been attested in the last 4000 years (Galili and Nir, 1993; Sivan et al., 2001).

Recent crustal movements, tectonism in Crete versus isostasy in the Pacific

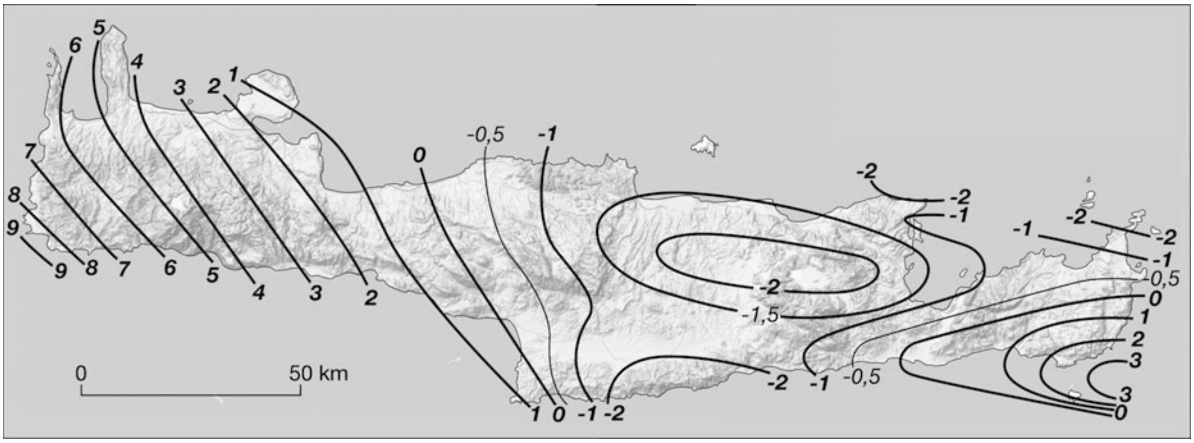
Western Crete was uplifted by up to 9 m in the fourth to fifth centuries AD (Stiros, 2010). At the scale of the Eastern Mediterranean, a cluster of coastal uplifts is attested by radiocarbon and archaeological data around this time. Detailed analysis of geological, historical, and archaeological data suggests that a major earthquake in Crete was responsible for coastal uplift in 365 AD. Despite significant changes in the coastal morphology, widespread destruction, and human loss of life, the 365 AD earthquake was not responsible for any major cultural change in Cretan society (Figure 3).

In a different crustal context, many studies of the Pacific islands suggest that relative sea-level fall has driven cultural change during the 3000-year history of human settlement. This is notably the case for the Lapita culture, which was dependent on coral-reef foraging but disappeared almost simultaneously around 600 BC (Nunn, 2005, 2007a; Carson, 2008). Most colonizing Lapita settlements were established on coastal fringes, perhaps on sandspits or sand-floored reef flats. As relative sea level fell and sediment accreted, these areas emerged inducing changes in settlement character and distribution (Nunn and Heorake, 2009). It is also clear that around 1300 AD, there was a rapid fall in relative sea level of 70–80 cm that induced food shortages in coastal areas across the Pacific Islands region and led to an abandonment of coastal settlements in favor of upland fortified settlements (Nunn, 2007b; Field and Lape, 2010). Environmental change was therefore an important cause of societal transformation during the prehistory of the Pacific Islands.

Geoarchaeology of Holocene coastal changes, from marine transgression to coastal progradation

Glacio-eustatic sea-level rise after the Last Glacial Maximum brought about worldwide flooding of coastal areas, controlling the evolution of marine embayments, fluvial mouths, and rocky coasts. By contrast, its significant deceleration during mid-Holocene times resulted in shoreline progradation, which was particularly pronounced along sediment-rich clastic coasts.

These shoreline modifications forced ancient societies to adapt their settlements continuously to the evolving landscape. Such rapid changes in sedimentary environments have been investigated in detail throughout the world using many methods and disciplines, including



Paleoshores (Lakes and Sea), Figure 3 Holocene land-level changes in Crete (After Kelletat (1991), and Stiros (2010)). Western Crete has been generally rising and eastern Crete sinking; numerical indicators are in meters.

geography, geomorphology, geology, biology, and archaeology. These studies have demonstrated that Holocene sea-level rise led to a general marine transgression, which was later countered by a strong progradational trend on alluvial-rich coasts that in turn slowed the rate of sea-level rise due to an increase in sediment yields from fluvial systems. During the last 3000 years, these sediment yields were enhanced by greater erosion rates due mainly to human-induced impacts on soil, vegetation, and fluvial systems.

All over the world, extensive coastal changes have played out on deltas, which act as depocenters storing large volumes of sediment produced by terrestrial erosion and delivered to the coast by fluvial systems. Deltas constitute excellent geo-archives for the study of settlement phases and coastal deformations. Paleogeographical studies have been important in developing new scenarios for delta and floodplain evolution. For example, Brückner (2005), Brückner et al. (2005, 2006), and many others have investigated the evolution of a number of eastern Mediterranean deltas during the last six millennia. The spatial and temporal evolution of the deltas has been reconstructed using geoarchaeology, combining delta stratigraphy and geomorphology with archaeological sources. For example, the siltation of the seaport of Ephesus (Kraft et al., 2007) was associated with the progressive deltaic growth of the Küçük Menderes (Kaystros) river and its tributaries. Ancient Troy, too, overlooked a large marine bay that has gradually silted up with sediment from the advancing Karamenderes (Scamander) and Dümrek (Simois) river deltas, weakening the city's strategic position (Kraft et al., 2003) (Figure 4).

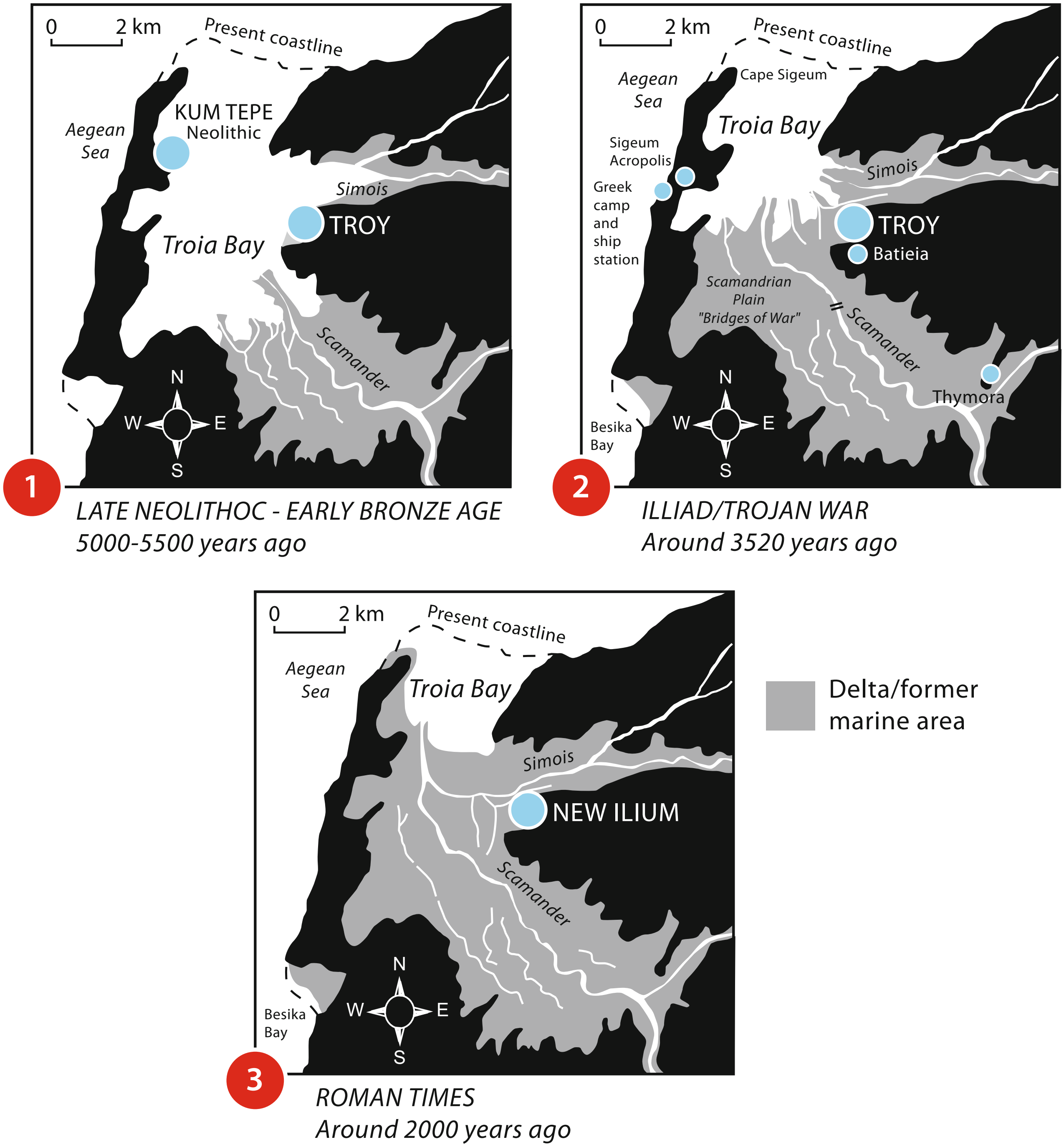
In Greece, Vött et al. (2007) have shown precise evidence for delta growth, based on chronostratigraphic data. The shipsheds of Oiniadai, dating to the fifth–third centuries BC, are today located 9 km inland on the Acheloos River (Acarnania) delta attesting to considerable coastal changes since the mid-Holocene. It has been demonstrated that Oiniadai's ancient shipsheds were accessible to the sea via a lagoon (Figure 5).

During the past 30 years, an acceleration in RSL rise and upstream sediment trapping by fluvial dams has led to accelerated erosion that has exposed archaeological remains, such as in Gaza (Morhange et al., 2005) and Tunisia (Trousset et al., 2004). Although coastal progradation has been the general trend during the past few millennia, many coastlines are, paradoxically, undergoing erosion linked to a human-induced decline in sediment supply that is currently destroying a great number of coastal sites.

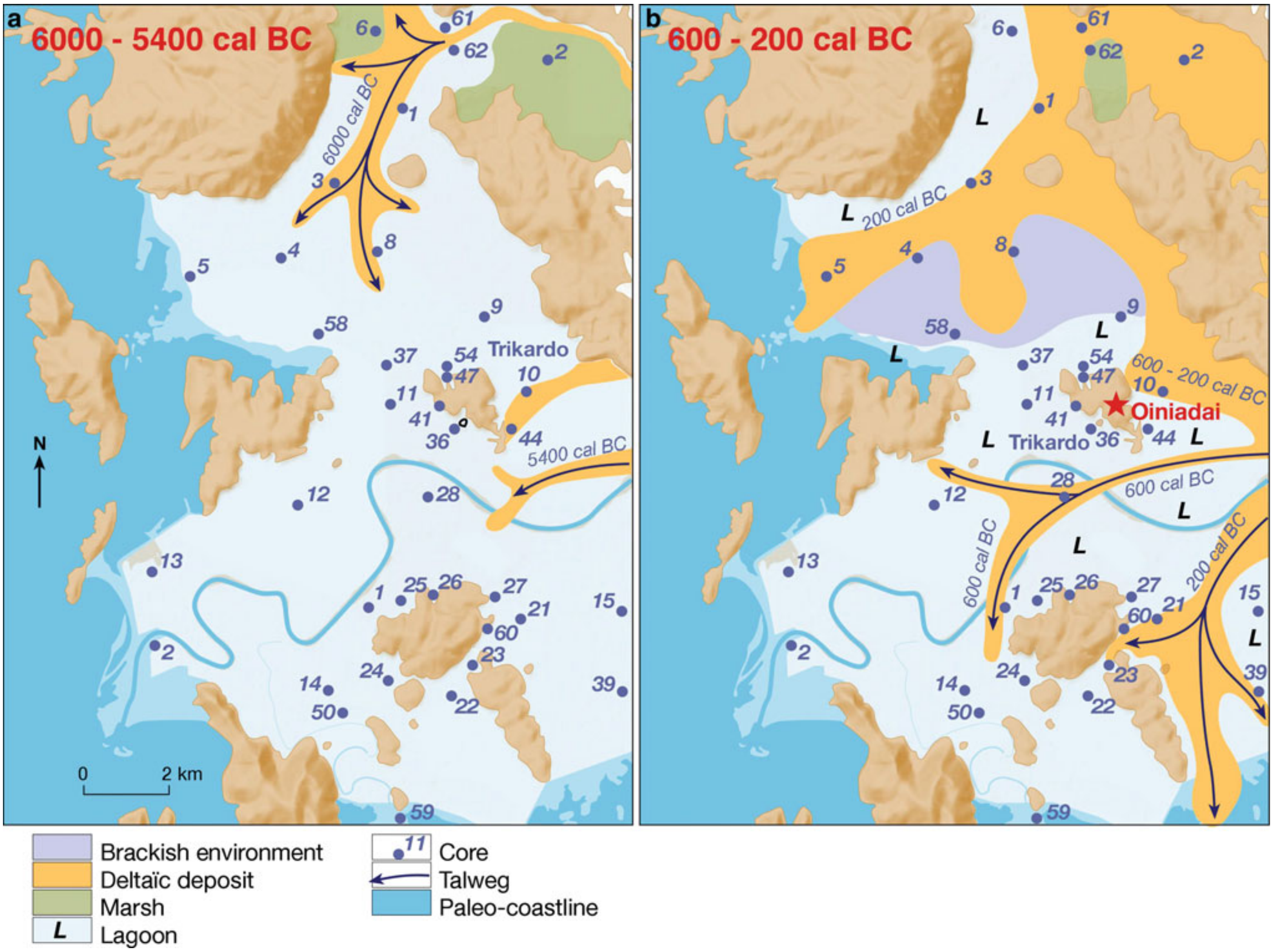
Lacustrine geoarchaeology: a long-standing controversy

Archaeological investigations have shown that lakeshores were attractive areas for ancient societies not only in Europe, where the sub-Alpine area has famously yielded Neolithic and Bronze Age lake dwellings, but also in other parts of the world, such as the many pre-Hispanic sites around the lakes of South and Central America. Because of the abundance of limestone rocks in their catchment area, most sub-Alpine lakes are characterized by a littoral platform at least partly composed of carbonate lake marl. In the shallow water on the surface of these littoral platforms, the remains of Neolithic and Bronze Age villages were discovered in the mid-nineteenth century, first in Switzerland and then rapidly all around the Alps in France, Germany, Austria, Italy, and Slovenia. Up until the late 1970s, these discoveries were controversial and vigorously debated: how could one explain settlement remains below present water level?

The mid-nineteenth-century Swiss researcher F. Keller interpreted the hundreds of wooden posts emerging from lake sediments as piles supporting platforms for lake dwellings (Figure 6). This hypothesis assumed that lake level and climate had not varied since the Neolithic period.



Paleoshores (Lakes and Sea), Figure 4 Paleogeography of the coastal area around Troy (Adapted from Kraft et al. (2003)) made famous by Homer's epic Greek poem the *Iliad*. At the time the *Iliad* is set, more than 3000 years ago, Troy overlooked a vast marine embayment that has since been infilled by sediments from the Scamander and Simois rivers. The archaeological remains at Troy today lie more than 6 km from the present coastline and bear testimony to the rapid changes in geography that can take place on deltaic systems with high sediment supply.

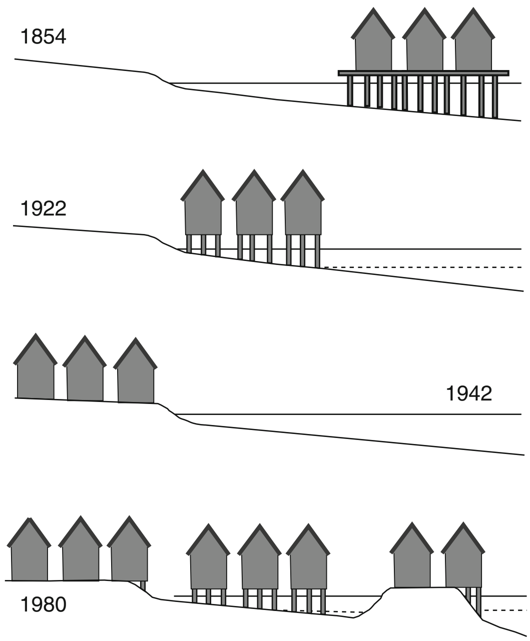


Paleoshores (Lakes and Sea), Figure 5 Progradation of the Acheloos River delta since 6000 years BP and location of the ancient seaport of Oiniadai (northwestern Greece), from Vött et al. (2007). The numbers denote core locations used in the paleogeographical reconstruction.

In the first half of the twentieth century, investigations by the German H. Reinerth led to a reinterpretation. On the basis of careful archaeological excavations and observations of architectural structures in the lakes Federsee and Bodensee (Germany), Reinerth postulated that the prehistoric lakeshore dwellings had been built directly upon the ground, or with slightly raised floors to accommodate seasonal floods, when the lake level was lower than today due to phases of drier climate. Reinerth's proposal was also consistent with the first paleoclimatic reconstructions developed for the Holocene period by the Scandinavian palynologists A. Blytt and R. Sernander, as well as by the palynologist H. Gams, and the geologist R. Nordhagen in Central Europe.

In the mid-twentieth century, a group of German and Swiss archaeologists led by O. Paret and E. Vogt went even further and affirmed that prehistoric lake dwellings had never existed, relegating them to mere myths. Neolithic and Bronze Age villages were built on the ground when lake levels were lower than today due to drier subboreal climatic conditions.

Since the 1970s, the adoption of more rigorous archaeological techniques, in addition to exceptional findings such as the Bronze Age settlements of Fiavé-Carrera in northern Italy (Perini, 1994), has progressively demonstrated that a great diversity of lakeshore dwellings developed during the Neolithic and Bronze Age around the Alps. The French archaeologist P. Pétrequin (Pétrequin and Pétrequin, 1988) has even shown that all types may have coexisted in the same village! As the debate on sub-Alpine prehistoric lake dwellings gradually abated, paleoclimatic investigations undertaken during the last three decades have provided detailed insights into Holocene climate history. These studies have shown that the last 11,700 years have been punctuated by successive centennial-scale phases of higher and lower lake levels



Paleoshores (Lakes and Sea), Figure 6 Successive interpretations of Neolithic and Bronze Age lakeshore villages in the sub-Alpine zone (Modified from Schlichtherle and Wahlster (1986)).

in West-Central Europe, in response to various forcing factors (Berglund, 1986; Magny, 2004, 2006).

Lakeshore archaeological sites and past environmental conditions

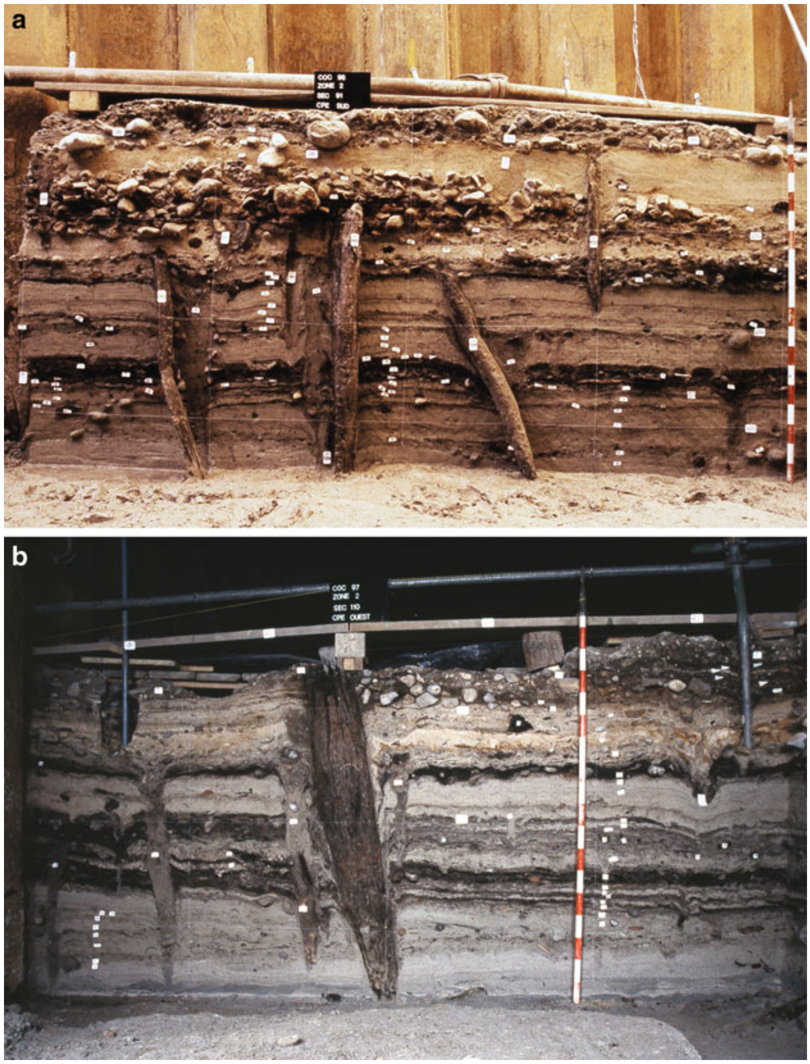
Despite these long-standing controversies regarding the general interpretation of sub-Alpine prehistoric lake dwellings, present-day investigations now operate within a more diverse and developed scientific framework. Generally, geoarchaeological studies have focused on the reconstruction of environmental conditions within these prehistoric villages built along the shores of sub-Alpine lakes. On one hand, this has entailed reconstruction of past positions of (and changes in) the water table during settlement phases in order to make more informed interpretations of architectural structures and/or to explain successive occupation and abandonment phases observed at a site. On the other hand, this has also involved the reconstruction of site paleogeography and past configurations, in addition to the general climatic and human contexts. The following section provides a brief overview of the types of proxies and strategies used in geoarchaeological studies of lakeshore sites, looking not only at reconstructions of local environmental conditions but also at the explorations into regional interactions between climate, environment, and land use.

As illustrated in Figure 7, the stratigraphic sections exposed during archaeological excavations of lakeshore sites often reveal sediment sequences displaying an alternation of layers resulting from natural lacustrine sedimentation and anthropogenic activities. Such sediment sequences reflect the successive phases of occupation and abandonment of the site by former agricultural societies. Moreover, the archaeological layers are also characterized by a more or less marked juxtaposition of anthropogenic deposits with natural sediments, which may indicate lake transgressions during the village occupation depending on both the architectural structures (houses directly on the ground or with raised floors) and the height of the water table (sensitivity to seasonal floods).

In the field, a key prerequisite for paleoenvironmental studies at lakeshore sites is the establishment of long stratigraphic sections and/or core transects within and outside the archaeological excavations, to probe the general environmental context of the site (Fouache et al., 2010). This provides evidence for phases marked by an extension of allochthonous terrestrial influxes (lowering of the water table) and those characterized by lake-dominated sediments (rising water table) (Figure 8). This also highlights layer geometry, lateral variations in lithofacies, local sediment hiatuses, stratigraphic unconformities, and sedimentation limits that can be used to reconstruct (1) the paleogeographical context of a site, as shown by investigations at Lake Clairvaux in the Jura Mountains of eastern France (Figure 9) or at the former Lake Texcoco in the basin of Mexico (Lamb et al., 2009) and (2) past variations in the lake level, as demonstrated by lake-level studies at Lake Chapala in Central America (Davis, 2003). Similarly, multiple littoral cores studied in the Upper Lerma Basin (Central Mexico) have shown how the construction of man-made islands reached a peak around 550–900 AD during a phase of shallow water and how an increase in lake level around 1100 AD may have led to the abandonment of this living strategy (Caballero et al., 2002). High-resolution seismic investigations based on GPS positioning offer an additional tool to produce reflection profiles, with a vertical resolution of 0.2 m (Chapron et al., 2005; Anselmetti et al., 2007; Chapron, 2008).

Finally, such a strategy helps to pinpoint relevant sites for sampling and analyses, based on sediment hiatuses as well as keeping in mind constraints linked to the types of proxies used for analyses.

Regarding the analyses, various proxies are available within sediment archives that can be used to reconstruct past lake levels. Beginning with the Swedish researcher T. Nilsson in the 1930s, then further developed by Digerfeldt (1986, 1988), Birks (1980), Jacomet (1985), and Hannon and Gaillard (1997), the first type of approach is based on the analysis of plant macrofossils from cores along a transect oriented perpendicular to the shore. This transect yields information useful in reconstructing changes in the spatial distribution of aquatic vegetation belts that reflect water depth (successive zones of emergent, floating-leaved, and submerged vegetation belts that fan outward from the shore). Thus, a decrease in water depth (lake-level lowering) leads to an outward extension

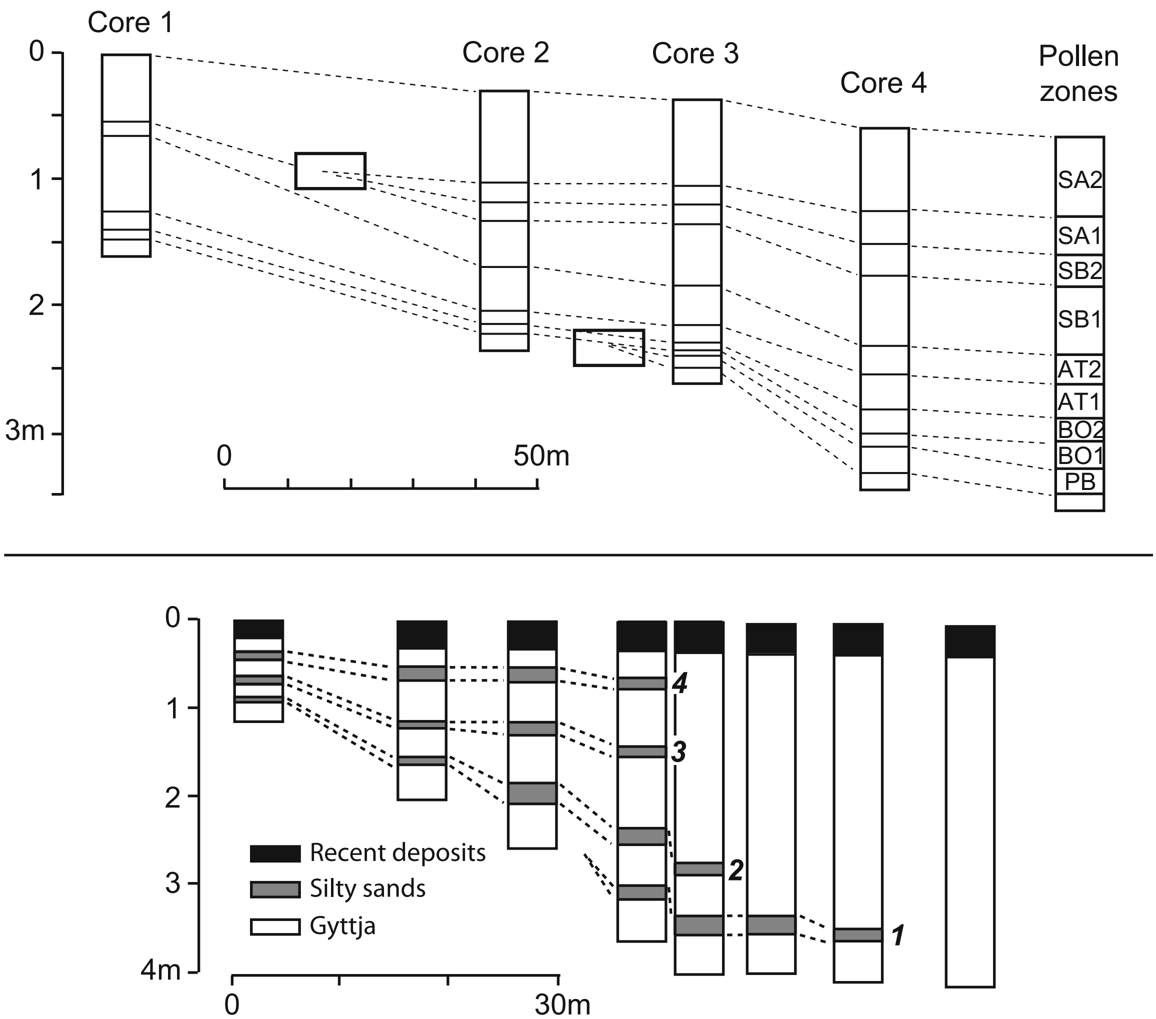


Paleoshores (Lakes and Sea), Figure 7 (**a**) and (**b**) show two stratigraphic sections at an archaeological lakeshore site from Concise, Lake Neuchâtel in Switzerland (photograph by P. Muller, Section de l'Archéologie Cantonale Vaudoise, in Magny (2008)). Note the alternation of (1) dark organic archaeological layers sedimented during the occupation phases and (2) light (carbonate) lake-marl layers deposited during the intermediate abandonment phases. Also note remains of vertical wood posts used by prehistoric people for the construction of houses.

of macrophytes, while an increase in water depth (rising lake level) leads to their inward displacement.

Another similar method of reconstruction using core transects is based on a combination of several sediment markers as follows:

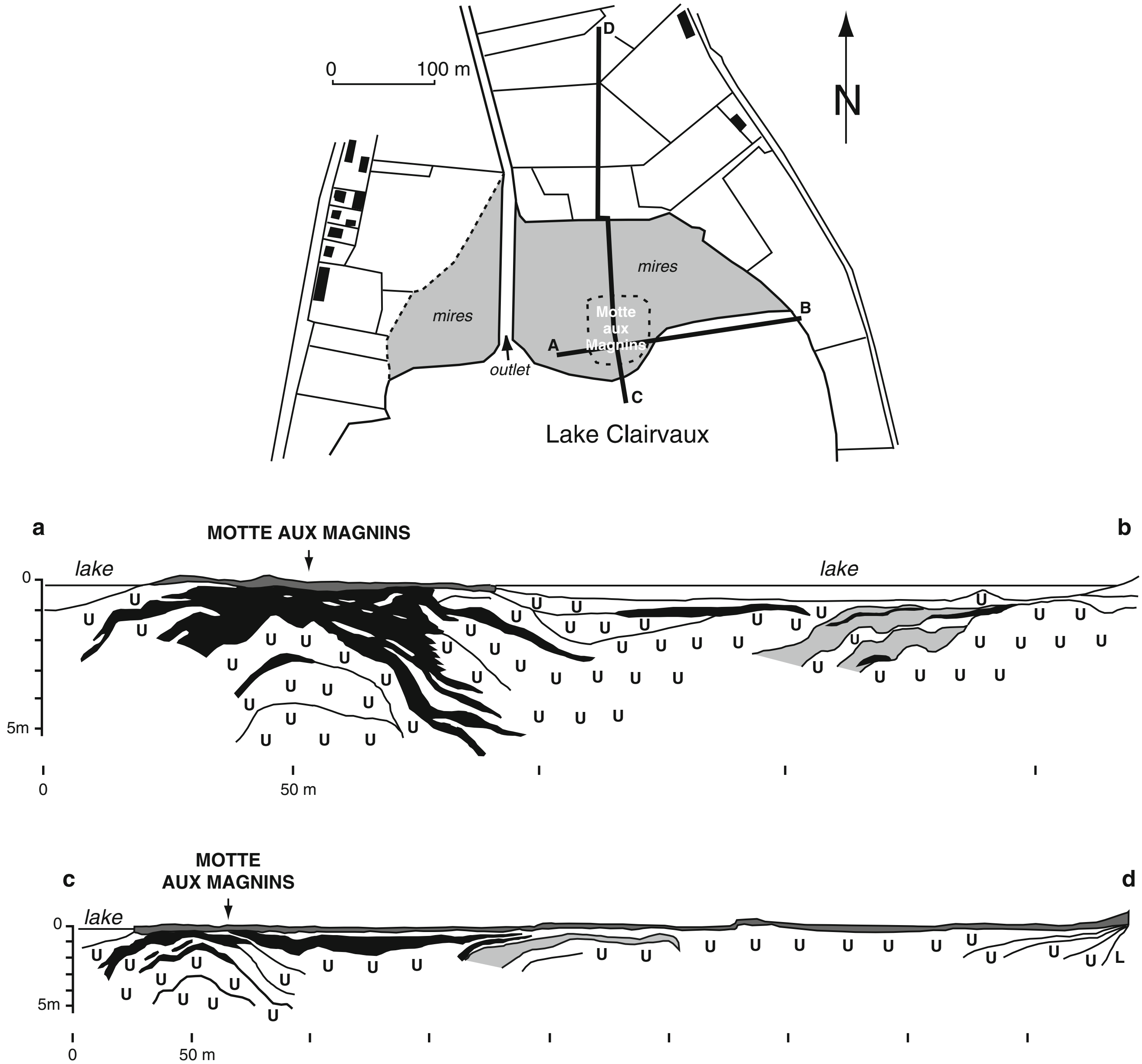
1. Grain-size analyses: coarser deposits correspond to nearshore areas, characterized by shallower water and higher hydrodynamics.
2. Lithology: silty (carbonate) lake marl is deposited in lake water, whereas organic deposits such as coarse gyttja, peat, and anmoor (hydromorphic soil with high humic content) reflect nearshore areas (eulittoral zone, littoral mire). Lake-level lowering results in an outward extension of organic lithofacies possibly associated with sand (terrestrial influxes over the margins of the lake basin favored by lake-level lowstands), while a rise in lake level results in their inward retreat (Figure 8). Variations in the humification of littoral organic deposits may also provide further indications on the more or less pronounced drying of a site during a lake-level lowering.
3. Macroscopic components of lake marl: it has been shown (Magny, 2004, 2006) that in carbonate lakes, the coarser fractions (>0.2 mm) of lake marl are mainly composed of (a) carbonate concretions of biochemical origin, (b) mollusk tests, and (c) plant



Paleoshores (Lakes and Sea), Figure 8 Upper panel: core transect established in Lake Trummen, southern Sweden (Modified from Digerfeldt (1986)). The section shows two distinct periods of lower sediment limit (*rectangles*) and associated sediment hiatuses (*thick lines* in cores 1 and 2) indicating lower lake level at phases PB–BO1 (Preboreal to Boreal 1) and SB1–2 (Subboreals 1–2). At both times, low water level prevented lacustrine sedimentation above the shoreline. *Lower panel*: core transect of Lake Växjösjon, southern Sweden (Modified from Digerfeldt (1986)). Sandy-silty layers mark phases of lower lake level favoring an extension of (allochthonous) terrestrial minerogenic material within the lake basin. Gyttja, marking the lake margins, is a mud produced from the aerobic decay of peat.

macroremains. The concretions can be divided into several morphotypes (Figure 10). Modern analogue studies have demonstrated that, in the >0.5 mm fraction, each morphotype shows a specific spatial distribution from the shore to the extremity of the littoral platform, with the successive domination of oncolites (nearshore areas with shallow water and a high-energy environment), cauliflower-like forms (littoral platform), platelike concretions (encrustations of leaves from the Potamogetonion and Nymphaeion belts), and finally tubelike concretions (stem encrustations from the Characeae belt on the platform slope). In addition to variations in the assemblages of carbonate concretions, the relative frequency of plant macroremains and mollusk shells provides further information on the depositional environment. The abundance of mollusk shells increases toward the shore, as do vegetal remains partly inherited from littoral vegetation and mires – particularly woody plant remains and particles of anmoor (a hydromorphic soil with up to 30 % humus content). After wet sieving, the macroscopic components of the >0.5 mm fraction are identified and counted using a binocular microscope.

4. Geometric micro-unconformities that are visible to the unaided eye resulting from erosion or nondeposition

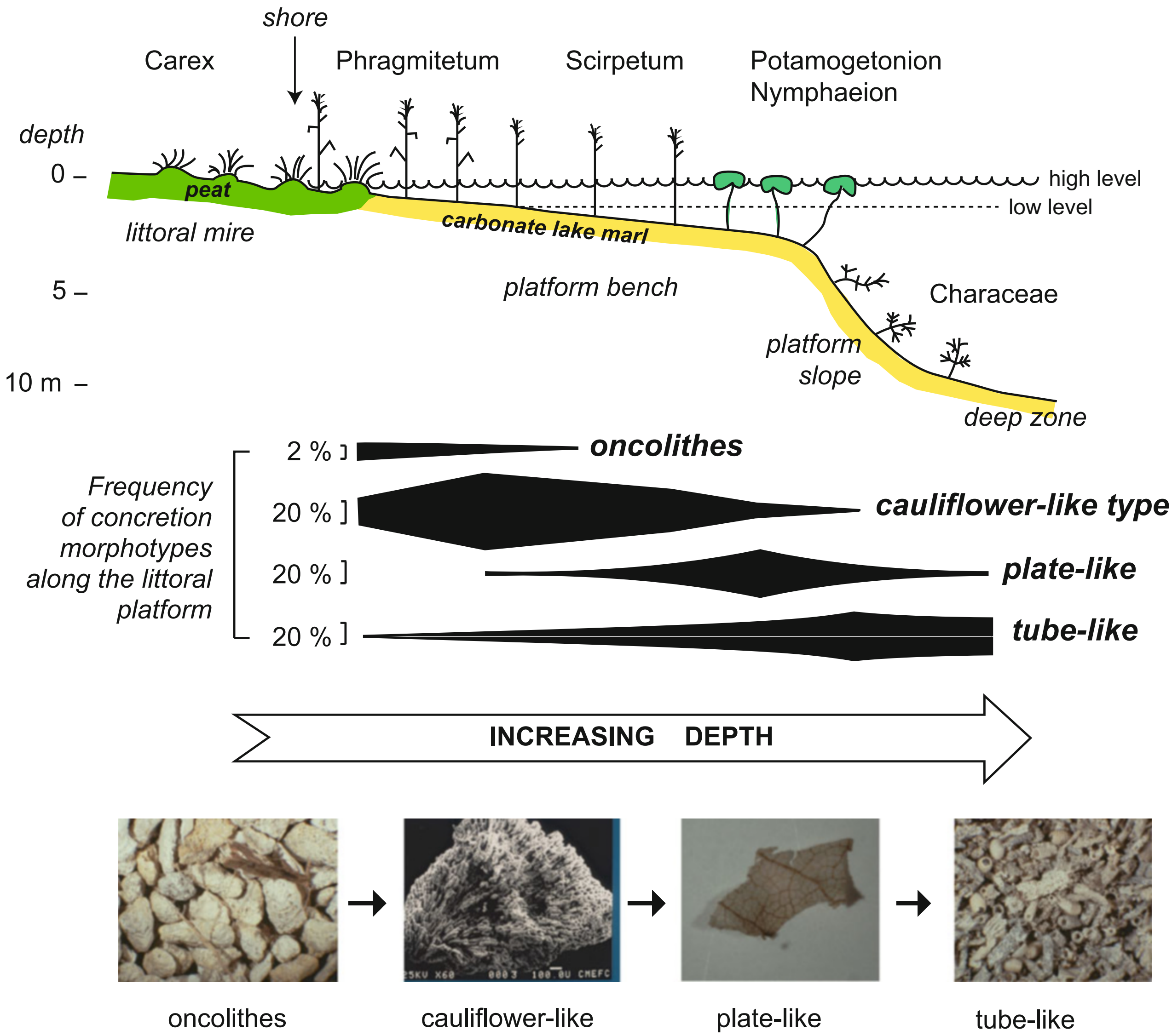


Paleoshores (Lakes and Sea), Figure 9 Reconstruction of the paleogeographical changes at the northern extremity of Lake Clairvaux, Jura Mountains in eastern France, using core transects. Note that the site of Motte aux Magnins (indistinct within the present-day northern littoral mires) was an island during the mid-Neolithic (Magny, 1991). The *arrow* shows the intersection between the stratigraphic sections *AB* and *CD. Black*, archaeological layers; *dark gray*, peat; *light gray*, gyttja; U, carbonate lake marl; L, silts.

(lake-level lowering), or micro-shrinkage cracks observed along core profiles, offer additional information about sediment deposition.

Other proxies have been used to reconstruct past variations in the water table from Holocene sediment sequences in lakes and mires (Berglund, 1986), including changes in mollusk assemblages (Clerc et al., 1989), diatoms and cladocera (Hyvärinen and Alhonen 1994; Korhola et al., 2005), chironomids (Kurek and Cwynar, 2009), and testate amoebae (Charman et al., 2007).

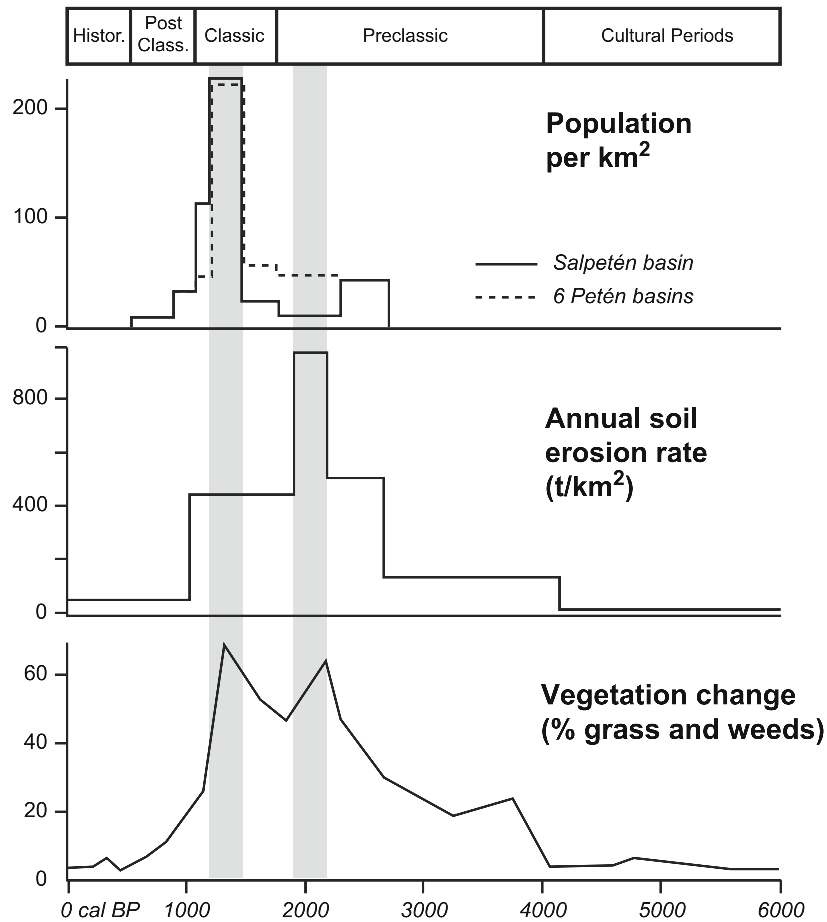
The study of archaeological layers may be more time-consuming due to a possible dilution of natural elements by anthropogenic material (organic and mineral). Micromorphology offers an additional means to study archaeological layers using microscopic examination of loose sediments impregnated with epoxy resin in thin section.



Paleoshores (Lakes and Sea), Figure 10 Section showing the distribution of carbonate concretion morphotypes along the littoral platform of Lake Clairvaux (Jura Mountains) in relation to morphology and vegetation zones. The relative frequency of each morphotype is indicated as a percentage of the sample components (Modified, after Magny (2006)).

Such a microscopic analysis used at Marin/Les Piécettes (Lake Neuchâtel, Switzerland) has revealed depositional characteristics similar to those of a lake-margin marsh, with soil formation processes, advanced decomposition of organic matter, and traces of bioturbation. Micromorphology can also provide a very high-resolution record of successive events with an accumulation of occupational remains, dismantling or reconstruction, trampling by inhabitants, and reworking by lake water (Guélat and Honegger, 2005).

Finally, the study of sediment archives from the deepest areas of lacustrine basins also provides useful continuous records of regional interest to complement local data deriving from a lakeshore archaeological site (Arnaud et al., 2005). Magnetic susceptibility measurements, geochemical (isotopes, XRF), and mineralogical analyses, in addition to pollen and charcoal studies, offer the opportunity to establish continuous records not only for past variations in environmental and climatic conditions but also for human impact and land use history. Thus, paleoenvironmental and archaeological data obtained from a littoral site may be seen in a more general (i.e., regional), long-term perspective. As an example, investigations undertaken by Anselmetti et al. (2007) from a deep core at Lake Salpetén (Guatemala) have revealed how peak soil erosion rates may have occurred not during but several centuries



Paleoshores (Lakes and Sea), Figure 11 Annual soil erosion rates compared with the population densities in the Salpetén region in Guatemala.

before the period of maximum population density in the ancient Maya zone (Figure 11). Cross-correlations between deep cores and littoral sediment profiles need to be based on high-resolution chronological frameworks (Vannière et al., 2008).

Conclusion: should greater attention be paid to anthropological themes?

Multidisciplinary approaches can be difficult and complicated to implement; however, geoarchaeological methods have evolved by integrating new geochemical and physical techniques that have improved the ability of researchers to date, delineate, and interpret the different aspects of coastal and lake excavation sites. The convergence of many disciplinary inquiries has led to more accurately established chronologies and greater understanding of past environment and human behavior.

The role of natural hazards and the evaluation of paleorisks are two questions that have received significant focus in recent years. Present neo-catastrophic research bias has falsely led public audiences into thinking that ancient societies lived and developed under the constant threat of upheavals caused by natural disasters. This overly simplistic outlook masks the true problems of environmental vulnerability faced by human societies since prehistoric times. Coastal areas have changed dramatically through time, and their impact has been significant to local populations, but geoarchaeological studies must assess coastal vulnerability over long intervals (Morhange and Marriner, 2011). As Leveau (2006) has stated, the history of ancient coastlines can no longer be written using ancient texts describing calamities as the sole source of information, as was the case in the nineteenth century. During the last three decades, the development and application of geoscience techniques to such problems have radically changed our perception of the history of coastal and lacustrine shorelines.

Bibliography

Anselmetti, F. S., Hodell, D. A., Ariztegui, D., Brenner, M., and Rosenmeier, M. F., 2007. Quantification of soil erosion rates related to ancient Maya deforestation. *Geology*, **35**(10), 915–918.

Arnaud, F., Revel, M., Chapron, E., Desmet, M., and Tribovillard, N., 2005. 7200 years of Rhône river flooding activity in Lake Le Bourget, France: a high-resolution sediment record of NW Alps hydrology. *The Holocene*, **15**(3), 420–428.

Auriemma, R., and Solinas, E., 2009. Archaeological remains as sea level change markers: a review. *Quaternary International*, **206** (1–2), 134–146.

Bailey, G. N., 2004. World prehistory from the margins: the role of coastlines in human evolution. *Journal of Interdisciplinary Studies in History and Archaeology*, **1**(1), 39–50.

Bailey, G. N., and Flemming, N. C., 2008. Archaeology of the continental shelf: marine resources, submerged landscapes and underwater archaeology. *Quaternary Science Reviews*, **27** (23–24), 2153–2165.

Bailey, G., Carrión, J. S., Fa, D. A., Finlayson, C., Finlayson, G., and Rodríguez-Vidal, J. (eds.), 2008. *The Coastal Shelf of the Mediterranean and Beyond: Corridor and Refugium for Human Populations in the Pleistocene*. Quaternary Science Reviews, Elsevier, Vol. 28, pp. 23–24.

Berglund, B. E., 1986. *Handbook of Holocene Palaeoecology and Palaeohydrology.* Chichester: Wiley.

Birks, H. H., 1980. *Plant Macrofossils in Quaternary Lake Sediments*. Archiv für Hydrobiologie 15. Ergebnisse der Limnologie 15. Stuttgart: Schweizerbart'sche Verlagsbuchhandlung.

Brückner, H., 2005. Holocene shoreline displacements and their consequences for human societies: the example of Ephesus in Western Turkey. In Fouache, E., and Pavlopoulos, K. (eds.), *Sea Level Changes in Eastern Mediterranean during Holocene: Indicators and Human Impacts*. Berlin: Gebrüder Borntraeger. Zeitschrift für Geomorphologie, N.F. Supplementband, Vol. 137, pp. 11–22.

Brückner, H., Vött, A., Schriever, M., and Handl, M., 2005. Holocene delta progradation in the eastern Mediterranean – case studies in their historical context. *Méditerranée*, **104**, 95–106.

Brückner, H., Müllenhoff, M., Gehrels, R., Herda, A., Knipping, M., and Vött, A., 2006. From archipelago to floodplain – geographical and ecological changes in Miletus and its environs during the last six millennia (Western Anatolia). In Eitel, B. (ed.), *Holocene Landscape Development and Geoarchaeological Research*. Berlin: Gebrüder Borntraeger. Zeitschrift für Geomorphologie, N.F. Supplementband, Vol. 142, pp. 63–83.

Caballero, M., Ortega, B., Valadez, F., Metcalfe, S. E., Macias, J. L., and Sugiura, Y., 2002. Sta. Cruz Atizapán: A 22-ka lake level record and climatic implications for the late Holocene human occupation in the Upper Lerma Basin, Central Mexico. *Palaeogeography Palaeoclimatology Palaeoecology*, **186** (3–4), 217–235.

Carson, M. T., 2008. Correlation of environmental and cultural chronology in New Caledonia. *Geoarchaeology*, **23**(5), 695–714.

Chapron, E., 2008. Les environnements sédimentaires récents du Lac du Bourget. In Jacquet, S., Domaizon, I., Poulenard, J., and Arnaud, F. (eds.), *Autour du lac du Bourget: Actes du colloque pluridisciplinaire, le Bourget-du-Lac, 15–17 mai, 2006*. Le Bourget-du-Lac: Editions de la Page Blanche, pp. 27–34.

Chapron, E., Arnaud, F., Noël, H., Revel, M., Desmet, M., and Perdereau, L., 2005. Rhone River deposits in Lake Le Bourget: a proxy for Holocene environmental changes in the NW Alps, France. *Boreas*, **34**(4), 404–416.

Charman, D. J., Blundell, A., and ACCROTELM Members, 2007. A new European testate *amoebae* transfer function for palaeohydrological reconstruction on ombrotrophic peatlands. *Journal of Quaternary Science*, **22**(3), 209–221.

Chorley, R. J., Beckinsale, R. P., and Dunn, A. J., 1964. *The History of the Study of Landforms; or, The Development of Geomorphology, volume 1. Geomorphology before Davis*. London: Methuen.

Church, J. A., Woodworth, P. L., Aarup, T., and Wilson, W. S., 2010. *Understanding Sea-Level Rise and Variability.* Chichester: Wiley-Blackwell.

Clerc, J., Magny, M., and Mouthon, J., 1989. Histoire d'un milieu lacustre du Bas-Dauphiné: le Grand-Lemps. Etude palynologique des remplissages tardiglaciaires et holocènes et mise en évidence de fluctuations lacustres à l'aide d'analyses sédimentologiques et malacologiques. *Revue de Paléobiologie*, **8**(1), 1–19.

Davis, L. G., 2003. Geoarchaeology and geochronology of pluvial Lake Chapala, Baja California, Mexico. *Geoarchaeology*, **18**(2), 205–223.

Digerfeldt, G., 1986. Studies on past lake-level fluctuations. In Berglund, B. E. (ed.), *Handbook of Holocene Palaeoecology and Palaeohydrology*. Chichester: Wiley, pp. 127–143.

Digerfeldt, G., 1988. Reconstruction and regional correlation of Holocene lake-level fluctuations in lake Bysjön, South Sweden. *Boreas*, **17**(2), 165–182.

Elias, S. A., Short, S. K., Nelson, C. H., and Birks, H. H., 1996. Life and times of the Bering land bridge. *Letters to Nature*, **382**(6586), 60–63.

Field, J. S., and Lape, P. V., 2010. Paleoclimates and the emergence of fortifications in tropical Pacific islands. *Journal of Anthropological Archaeology*, **29**(1), 113–124.

Fleming, K., Johnston, P., Zwartz, D., Yokoyama, Y., Lambeck, K., and Chappell, J., 1998. Refining the eustatic sea-level curve since the Last Glacial Maximum using far- and intermediate-field sites. *Earth and Planetary Science Letters*, **163**(1–4), 327–342.

Flemming, N. C. (ed.), 2004. *Submarine Prehistoric Archaeology of the North Sea: Research Priorities and Collaboration with Industry.* New York: Council for British Archaeology. Research Report, Vol. 141.

Flemming, N. C., and Webb, C. O., 1986. Tectonic and eustatic coastal changes during the last 10,000 years derived from archaeological data. In Özer, A., and Vita-Finzi, C. (eds.), *Dating Mediterranean Shorelines*. Berlin: Gebrüder Borntraeger. Zeitschrift für Geomorphologie, Supplementband, Vol. 62, pp. 1–29.

Fouache, E., Desruelles, S., Magny, M., Bordon, A., Oberweiler, C., Coussot, C., Touchais, G., Lera, P., Lézine, A.-M., Fadin, L., and Roger, R., 2010. Palaeogeographical reconstructions of Lake Maliq (Korça Basin, Albania) between 14,000 BP and 2000 BP. *Journal of Archaeological Science*, **37**(3), 525–535.

Galili, E., and Nir, Y., 1993. The submerged Pre-Pottery Neolithic water well of Atlit-Yam, northern Israel, and its palaeoenvironmental implications. *The Holocene*, **3**(3), 265–270.

Galili, E., Weinstein-Evron, M., Hershkovitz, I., Gopher, A., Kislev, M., Lernau, O., Kolska-Horwitz, L., and Lernau, H., 1993. Atlit-Yam: a prehistoric site on the sea floor off the Israeli coast. *Journal of Field Archaeology*, **20**(2), 133–157.

Glacken, C. J., 1967. *Traces on the Rhodian Shore: Nature and Culture in Western Thought from Ancient Times to the End of the Eighteenth Century.* Berkeley: University of California Press.

Guélat, M., and Honegger, M., 2005. Micromorphology applied to lakeside settlement at Marin/Les Piécettes (Neuchâtel, Switzerland): analysis of anthropogenic clay accumulations. In Della Casa, P., and Trachsel, M. (eds.), *WES'04: Wetland Economies and Societies. Proceedings of the International Conference, Zurich, 10–13 March 2004*. Zurich: Chronos. Collectio Archæologica, Vol. 3, pp. 95–98.

Hannon, G. E., and Gaillard, M.-J., 1997. The plant-macrofossil record of past lake-level changes. *Journal of Paleolimnology*, **18**(1), 15–28.

Hyvärinen, H., and Alhonen, P., 1994. Holocene lake-level changes in the Fennoscandian tree-line region, western Finnish Lapland: Diatom and cladoceran evidence. *The Holocene*, **4**(3), 251–258.

Jacomet, S., 1985. *Botanische Makroreste aus den Sedimenten des neolithischen Siedlungplatzes AKAD-Seehofstrasse am untersten Zürichsee*. Zürich: Juris Druck and Verlag AG. Zürcher Studien zur Archäologie.

Kelletat, D., 1991. The 1550 BP tectonic event in the Eastern Mediterranean, as a basis for assuring the intensity of shore processes. In Paskoff, R. P., and Kelletat, D. (eds.), *Geomorphology and Geoecology: Coastal Dynamics and Environments*. Berlin: Gebrüder Borntraeger. Zeitschrift für Geomorphologie, Supplementband, Vol. 81, pp. 181–194.

Korhola, A., Tikkanen, M., and Weckström, J., 2005. Quantification of Holocene lake-level changes in Finnish Lapland using a - cladocera-lake depth transfer model. *Journal of Paleolimnology*, **34**(2), 175–190.

Kraft, J. C., Rapp, G. R., Kayan, I., and Luce, J. V., 2003. Harbor areas at ancient Troy: Sedimentology and geomorphology complement Homer's *Iliad. Geology*, **31**(2), 163–166.

Kraft, J. C., Brückner, H., Kayan, I., and Engelmann, H., 2007. The geographies of ancient Ephesus and the Artemision in Anatolia. *Geoarchaeology*, **22**(1), 121–149.

Kurek, J., and Cwynar, L. C., 2009. The potential of site-specific and local chironomid-based inference models for reconstructing past lake levels. *Journal of Paleolimnology*, **42**(1), 37–50.

Laborel, J., and Laborel-Deguen, F., 1994. Biological indicators of relative sea-level variations and of co-seismic displacements in the Mediterranean region. *Journal of Coastal Research*, **10**(2), 395–415.

Lamb, A. L., Gonzalez, S., Huddart, D., Metcalfe, S. E., Vane, C. H., and Pike, A. W. G., 2009. Tepexpan Palaeoindian site, Basin of Mexico: multi-proxy evidence for environmental change during the late Pleistocene-late Holocene. *Quaternary Science Reviews*, **28**(19–20), 2000–2016.

Lambeck, K., and Bard, E., 2000. Sea-level change along the French Mediterranean coast for the past 30 000 years. *Earth and Planetary Science Letters*, **175**(3–4), 203–222.

Lambeck, K., Esat, T. M., and Potter, E.-K., 2002. Links between climate and sea levels for the past three million years. *Nature*, **419**(6903), 199–206.

Leveau, P., 2006. Les littoraux de Gaule du Sud au premier Âge du Fer, du delta de l'Argens au delta de l'Aude, un état de la question. In Gori, S., and Bettini, M. C. (eds.), *Gli Etruschi da Genova ad Ampurias. Atti del XXIV Convegno di Studi Etruschi ed Italici, Marseille-Lattes, 26 settembre–1 ottobre 2002*. Pisa: Istituti Editoriali e Poligrafici Internazionali, pp. 47–60.

Magny, M., 1991. Une approche paléoclimatique de l'Holocène: Les fluctuations des lacs du Jura et des Alpes du Nord françaises. PhD thesis, Université de Franche-Comté, Besançon.

Magny, M., 2004. Holocene climatic variability as reflected by mid-European lake-level fluctuations, and its probable impact on prehistoric human settlements. *Quaternary International*, **113**(1), 65–79.

Magny, M., 2006. Holocene fluctuations of lake levels in west-central Europe: methods of reconstruction, regional pattern, palaeoclimatic significance and forcing factors. In Elias, S. A. (ed.), *Encyclopedia of Quaternary Science*. Amsterdam: Elsevier, Vol. 2, pp. 1389–1399.

Magny, M., 2008. Les variations holocènes du niveau du lac de Neuchâtel enregistrées par la séquence sédimentaire de Concise, et leurs relations avec les habitats du Néolithique et de l'âge du Bronze. In Winiger, A. (ed.), *La station lacustre de Concise 1. Stratigraphie, datations et contexte environnemental*. Lausanne: Cahiers d'archéologie romande. Cahiers d'Archéologie Romande, Vol. 111, pp. 79–109.

Masters, P. M., and Flemming, N. C. (eds.), 1983. *Quaternary Coastlines and Marine Archaeology: Towards the Prehistory of Land Bridges and Continental Shelves*. London: Academic.

Morhange, C., and Marriner, N., 2011. Palaeo-hazards in the coastal Mediterranean: a geoarchaeological approach. In Martini, I. P., and Chesworth, W. (eds.), *Landscapes and Societies: Selected Cases*. Dordrecht: Springer, pp. 223–234.

Morhange, C., Laborel, J., and Hesnard, A., 2001. Changes of relative sea level during the past 5000 years in the ancient harbor of Marseilles, Southern France. *Palaeogeography Palaeoclimatology Palaeoecology*, **166**(3–4), 319–329.

Morhange, C., Hamdan Taha, M., Humbert, J.-B., and Marriner, N., 2005. Human settlement and coastal change in Gaza since the Bronze Age. *Méditerranée*, **104**, 75–78.

Mörner, N.-A., 1996. Sea-level variability. In Kelletat, D., and Psuty, N. P. (eds.), *Field Methods and Models to Quantify Rapid Coastal Changes*. Berlin: Gebrüder Borntraeger. Zeitschrift für Geomorphologie, Supplementband, Vol. 102, pp. 223–232.

Nunn, P. D., 2005. Reconstructing tropical paleoshorelines using archaeological data: examples from the Fiji Archipelago, southwest Pacific. *Journal of Coastal Research*, **42**, 15–25, Special Issue.

Nunn, P. D., 2007a. Holocene sea-level change and human response in Pacific Islands. *Transactions of the Royal Society of Edinburgh, Earth and Environmental Sciences*, **98**(1), 117–125.

Nunn, P. D., 2007b. *Climate, Environment and Society in the Pacific during the Last Millennium*. Amsterdam: Elsevier.

Nunn, P. D., and Heorake, T. A., 2009. Understanding the place properly: palaeogeography of selected Lapita sites in the western tropical Pacific Islands and its implications. In Sheppard, P. J., Thomas, T., and Summerhayes, G. R. (eds.), *Lapita: Ancestors and Descendants*. Auckland: New Zealand Archaeological Association. New Zealand Archaeological Association Monograph, Vol. 28, pp. 235–254.

Perini, R., 1994. *Scavi archeologici nella zona palafitticola di Fiavé-Carera, Parte III*. Trento: Servizio Beni Culturali della Provincia Autonoma di Trento. Patrimonio storico e artistico del trentino, Vol. 10.

Perissoratis, C., and Conispoliatis, N., 2003. The impacts of sea-level changes during latest Pleistocene and Holocene times on the morphology of the Ionian and Aegean seas (SE Alpine Europe). *Marine Geology*, **196**(3–4), 145–156.

Pétrequin, A.-M., and Pétrequin, P., 1988. *Le Néolithique des lacs. Préhistoire des lacs de Chalain et de Clairvaux, 4000–2000 av. J.-C*. Paris: Errance.

Pirazzoli, P. A., 1976. Sea level variations in the northwest Mediterranean during Roman times. *Science*, **194**(4264), 519–521.

Pirazzoli, P. A., 1977. Sea level variations in the world during the last 2000 years. *Zeitschrift für Geomorphologie*, **21**(3), 284–296.

Pirazzoli, P. A., 1986. Marine notches. In Van de Plaasche, O. (ed.), *Sea-Level Research: A Manual for the Collection and Evaluation of Data*. Norwich: Geo Books, pp. 361–400.

Pirazzoli, P. A., 1991. *World Atlas of Holocene Sea-Level Changes*. Amsterdam: Elsevier. Elsevier Oceanography Series, Vol. 58.

Schlichtherle, H., and Wahlster, B., 1986. *Archäologie in Seen und Mooren: Den Pfahlbauten auf der Spur*. Stuttgart: Theiss Verlag.

Sivan, D., Wdowinski, S., Lambeck, K., Galili, E., and Raban, A., 2001. Holocene sea-level changes along the Mediterranean coast of Israel, based on archaeological observations and numerical model. *Palaeogeography Palaeoclimatology Palaeoecology*, **167**(1–2), 101–117.

Stiros, S. C., 2010. The 8.5 magnitude, AD365 earthquake in Crete: coastal uplift, topography changes, archaeological and historical signature. *Quaternary International*, **216**(1–2), 54–63.

Trousset, P., Slim, H., Paskoff, R., and Oueslati, A., 2004. *Le littoral de la Tunisie: Etude géoarchéologique et historique*. Paris: CNRS Editions.
Vannière, B., Colombaroli, D., Chapron, E., Leroux, A., Tinner, W., and Magny, M., 2008. Climate versus human-driven fire regimes in Mediterranean landscapes: the Holocene record of Lago dell'Accesa (Tuscany, Italy). *Quaternary Science Reviews*, **27** (11–12), 1181–1196.
Vött, A., Schriever, A., Handl, M., and Brückner, H., 2007. Holocene palaeogeographies of the central Acheloos River delta (NW Greece) in the vicinity of the ancient seaport Oiniadai. *Geodinamica Acta*, **20**(4), 241–256.

Cross-references

Inundated Freshwater Settings
Paludal Settings (Wetland Archaeology)
Shipwreck Geoarchaeology
Soil Micromorphology
Submerged Continental Shelf Prehistory

PALUDAL SETTINGS (WETLAND ARCHAEOLOGY)

Kristin Ismail-Meyer and Philippe Rentzel
Department of Environmental Sciences, Integrative Prehistory and Archaeological Science (IPAS), University of Basel, Basel, Switzerland

Definition

Wetlands are ecosystems created at the interface of terrestrial and aquatic environments. They arise due to inundation and accumulation of plant material dominated by anaerobic processes (Middleton, 1999, 7; Mitsch and Gosselink, 2007, 26; Burton and Tiner, 2009, 507; Keddy, 2010, 2). The Ramsar Convention of 1971 characterizes wetlands as follows: "Wetlands can be natural, permanent or temporary, with water that is static or flowing, fresh, brackish or salt. . ." (Middleton, 1999, 7; Burton and Tiner, 2009, 508; Dodds and Whiles, 2010, 86). Based on their hydrology, wetlands can be systematized into coastal wetlands within marine and estuarine systems (tidal marshes, mangrove wetlands, deltas), and inland freshwater wetlands within riverine, lacustrine, and palustrine systems (van der Valk, 2006, 7; Mitsch and Gosselink, 2007, 260; Lillie and Ellis, 2007, 3). Palustrine areas can be defined according to their dominant vegetation as follows: swamps are dominated by trees and marshes by herbaceous plants (cattail and reed beds). Both of them are often associated with river floodplains. Peatlands (bogs and fens) accumulate decaying organic matter from mosses and sedges (Dierssen, 2003, 202; Mitsch and Gosselink, 2007, 31; Dodds and Whiles, 2010, 95ff.; Keddy, 2010, 5ff.; Menotti, 2012, 11).

Archaeological sites can be found in wetland areas. After Nicholas (2012), waterlogged archaeological sites can be distinguished as "wet sites," like coastal, lacustrine, and riverine sites or as "wetland sites," located in swamps, marshes, and peatlands. Lakeside settlements are categorized within the latter, as they are placed at the amphibian interface between limnic and terrestrial environments (Menotti, 2012, 13f.).

Introduction

About 5 % of the land surface of the earth is covered by wetlands. Depending on the kind of water source and its position in the landscape, wetlands show a wide range of environments (van der Valk, 2006, 8; Menotti, 2012, 13f.). Wetland research is not covered by a single field but refers variously to limnology, hydrology, and estuarine and terrestrial ecology. This is also why wetland investigations require a multidisciplinary approach spread across several fields (Mitsch and Gosselink, 2007, 19).

Wetlands have always been important for people, as they were long utilized for resource procurement, e.g., reed, cattail, and moss cutting as building materials, as well as for food and fuel collection (Mitsch and Gosselink, 2007, 5; Nicholas, 2012, 762). Archaeological sites connected to wetlands play a very important role in archaeological research. Because of their waterlogged, anaerobic conditions, they may contain well-preserved archaeological remains in situ and offer great promise for reconstructions not only in archaeology and paleoenvironment but also in the diet and hygiene of people (Cole, 1995, 3; Kenward and Hall, 2004, 4, 2008, 585; Menotti, 2004; Larsson, 2007, 80; Menotti, 2012, 9f.).

Wetland archaeology is relevant in almost every part of the world (Menotti, 2004, 2012). In this contribution, the focus is on freshwater wetlands around lakes, where lakeside settlements developed during the Neolithic and Bronze Age in the Circum-Alpine region of Europe (Menotti, 2012). Bog and fen sites, which are common in Great Britain and Scandinavia, and hydric soils are not part of this contribution (see, e.g., Cole, 1992; Lillie, 2007; Mitsch and Gosselink, 2007, 169ff.; Menotti, 2012).

Prehistoric lakeside settlements have been known for more than 150 years (Cole, 1995, 3; Ruoff, 2004; Menotti, 2001, 2004, 2012), and since their discovery, questions concerning the depositional environment have been addressed using the archaeological sediments to obtain answers (e.g., Brochier, 1983; Jacomet, 1985; Brochier and Bocquet, 1991; Magny, 2004; Jacomet et al., 2004; Magny et al., 2012). Since 2011, 111 pile-dwelling sites from six countries around the Alps have been added to the UNESCO World Heritage List (http://whc.unesco.org/en/list/1363). Micromorphological investigations of lakeside settlements started in the early 1990s and are today often a part of the standard analyses for pile-dwelling sites (Krier, 1997; Wallace, 2000, 2003; Ismail-Meyer and Rentzel, 2004; Lewis, 2007; Karkanas et al., 2011; Ismail-Meyer et al., 2013; Ismail-Meyer, 2014).

Lakeside settlements span several depositional environments from terrestrial and paludal to littoral and limnic, and all reveal different features (Jacomet et al., 2004;

Mitsch and Gosselink, 2007, 29; Nicholas, 2012, 762). One of the most remarkable features of pile-dwelling sites is that they often contain a significant amount of organic accumulations, which in general are underlain and covered by deposits of limnic sediments. A main research issue is to explain the formation of those organic accumulations and their mostly excellent preservation in a changing environment. Geoarchaeological research provides hints to the site formation processes and environment of wetland sites between episodes of deposition and any subsequent or intermittent episodes of erosion (Menotti, 2012, 252). Recent multidisciplinary studies have produced archaeological results based on archaeobotanical, palynological, geoarchaeological, and dendrochronological analyses, leading to new insights into formation processes (Menotti, 2012, 267ff.; Heitz-Weniger, 2014; Ismail-Meyer, 2014; Bleicher, 2014; Pollmann, 2014; Jacomet et al., 2014; Wiemann and Rentzel 2015).

To understand the context of these special archaeological deposits, a look at natural wetland environments, especially peatlands, and their hydrology is essential. In this contribution, some important processes regarding anthropogenic accumulations under paludal conditions will be discussed by comparing them with natural processes in wetland environments.

Methods

There are several geoarchaeological methods for analyzing lakeside settlements. Bulk samples for sedimentological and geochemical approaches are taken on-site from representative zones. An example demonstrating such methodologies can be found in Braillard et al. (2004). The carbonate content is normally related to lake input or to ashy layers in an archaeological context. Using a binocular microscope, limnic carbonates can be separated into different types, such as “tubes,” “cauliflower carbonates,” and “plates,” which may give hints to the height of the lake level (Brochier, 1983; Magny, 2004; Magny et al., 2006; Digerfeldt et al., 2007; Magny et al., 2012). Sand content can be linked to regressions in the littoral area, inwash from the hinterland, or it can be of anthropogenic origin (Magny, 2004; Ismail-Meyer, 2014). Evaluation and interpretation of phosphate, humus, and organic content can be difficult because phosphate may have been partially washed out, humus formation may not have occurred normally, or other factors may have complicated the analysis. The pH reflects usually the near-lake environment (generally between 6 and 8), but it may differ across the anthropogenic accumulations (e.g., due to a locally acid milieu or possibly the presence of humic acids).

Good results can be obtained using micromorphological investigation. By analyzing thin sections, it is possible to observe the structure, layer composition, and degree of preservation of each deposit (FitzPatrick, 1993; Stoops, 2003; Goldberg and Macphail, 2006). It permits the reconstruction of lake levels, site formation processes, and environments during and after the deposition of sediments, and it demonstrates whether anthropogenic layers remain in situ or were reworked. Very delicate traces such as trampling features, ashes, and dung can be detected (Ismail-Meyer and Rentzel, 2004). The autofluorescence of different types of organic matter can be used to identify them (Goldberg and Macphail, 2006, 358). The determination of well-preserved organic matter in thin section is possible but difficult because of the randomness inherent in differing section planes. Thanks to a substantial literature, close cooperation with archaeobotanists, and the existence of reference sections, it is possible to identify wood, bark, twigs, leaves, moss, grass, and some of the most common seeds (Babel, 1975, 1985; Ismail-Meyer and Rentzel, 2004; Stolt and Lindbo, 2010; Ismail-Meyer, 2016). Scanning electron microscopy (SEM) methods and punctuated (spot) microchemical data allow the examination of materials at sizes smaller than 2 μm on uncovered thin sections (Goldberg and Macphail, 2006, 362).

Selecting an appropriate sampling strategy for micromorphological investigations of lakeside settlements is crucial. A site can be fairly complex (i.e., having several occupation layers, substantial depth, and variable preservation of the archaeological deposits), and it is therefore important to adapt the sampling strategy to the existing conditions. But the strategy depends also on the size of a site and if it is underwater. The right strategy might be to sample along transects from the lake toward the beach, within the area of best preservation, or following the floor plans of the houses (if known). Usually, cores or plastic boxes of about 50 cm height and at least 10–15 cm width are used in sampling for multidisciplinary analyses. Generally, it is important to sample the anthropogenic accumulations as well as the limnic sediments above and below, in order to reconstruct the regressions and transgressions of the lake. Until the opening of the samples for analysis, it is recommended that they be stored in waterproof containers under dark and cool conditions to prevent the growth of fungi and algae.

Photographs of freshly opened and cleaned profiles are important for documenting the stratigraphic sequence. A division of the sequences into layers (preferentially with the collaboration of an archaeobotanist and palynologist) and a description with special attention to carbonate and sand content are useful. The micromorphological subsampling of the profiles (anthropogenic and limnic sediments) for further investigations, including archaeobotany and palynology, can be done with smaller plastic boxes.

Features and processes in paludal environments

Lake environments are a result of many complex factors influencing the ecosystem, including limnological, geological, hydrological, geomorphological, and biological processes operating in the catchment area. These factors are mainly controlled by fluctuations of the groundwater table and/or lake level, due often to climatic influences, but in Western Europe over the last 7,500 years, humans have increasingly interacted with the environment (van der Valk, 2006, 13; Digerfeldt et al., 2007; Keddy, 2010, 270; Zolitschka et al., 2010, 90). The size of the wetland area (and the area of preserved, waterlogged, archaeological remains) depends on the local geomorphology, e.g., inclination and type of shore belt (Platt and Wright, 1991; Magny, 2004; Jacomet et al., 2004). Generally, the greater the long-term amplitude of water-level fluctuations in a lake, the larger the wetland area (Keddy, 2010, 68).

The main processes in wetland environments are accumulation, reworking, erosion, and desiccation, and they depend on the height of the lake level and/or groundwater table. In this contribution, these processes will be highlighted through the example of natural peatlands and compared to proper observations in lakeside settlements. The study results derive from eight pile-dwelling sites analyzed during the past 10 years in Switzerland: Arbon-Bleiche 3, Cham-Eslen, Zug-Riedmatt, Risch-Aabach, Stansstad-Kehrsiten, Wetzikon-Robenhausen, Hombrechtikon-Feldbach West, as well as Lake Luokesa in Lithuania (see Ismail-Meyer et al., 2013; Ismail-Meyer, 2014).

Paludal Settings (Wetland Archaeology), Figure 1 Zug-Riedmatt, Switzerland: Paludal Neolithic site (3200 cal BC) during geoarchaeological fieldwork at the archaeological excavation. In the foreground appears a dark organic layer of anthropogenic origin containing many vertical posts of different construction phases. Note the succession of gray, lumpy loam lenses interfingered with dark, organic occupation deposits (in the angle of the profile). On top, the archaeological deposits are eroded and covered by light gray, laminated limnic sediments (Photograph by D. Brönnimann, Integrative Prehistory and Archaeological Science, IPAS, University of Basel).

Lake platform and limnic sediments

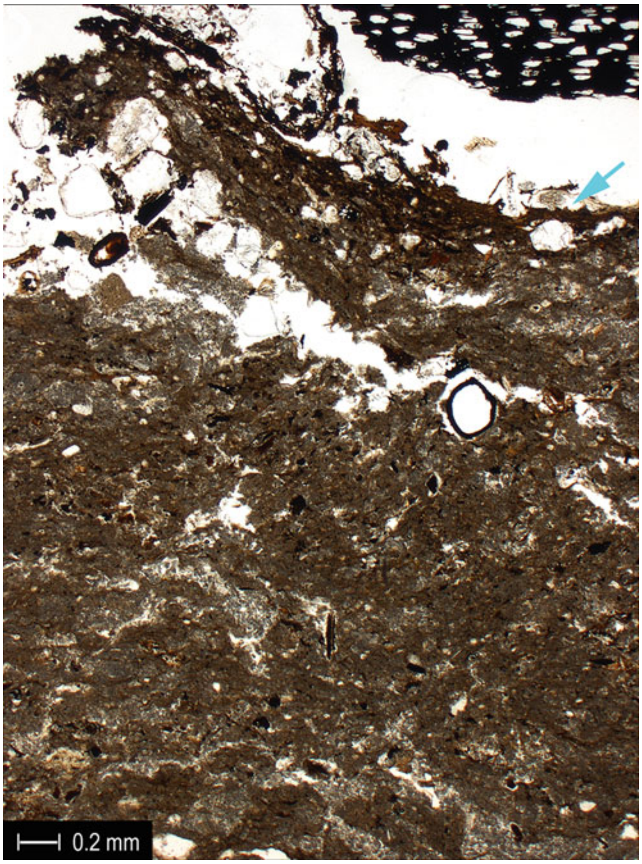
Lakeside settlements are usually deposited atop carbonate platforms along lakeshores (Figure 1). In shallow waters, carbonate precipitates as lake marl, formed mainly by different algae (mainly stonewort – Characeae), bacteria, and diatoms. Benches are formed due to progradational deposition (Murphy and Wilkinson, 1980; Platt and Wright, 1991; Freytet and Verrecchia, 2002; Magny et al., 2006). Undisturbed, layered lake marl accumulates in the deeper sublittoral zone in about 1–10 m water depth (Murphy and Wilkinson, 1980; Platt and Wright, 1991; Magny, 2004; Haas and Magny, 2004). The lowering of the lake level results in the reworking of this lake marl due to wave action and enrichment with sand (Platt and Wright 1991; Magny, 2004; Magny et al., 2006; Digerfeldt et al., 2007). Even small-scale water-level fluctuations may cause exposure of large areas depending on the slope of the shore area. In geological sections, the tops of such regressive sequences commonly show evidence of subaerial exposure (hiatus), e.g., alteration and fragmentation of mollusk shells (Platt and Wright, 1991, 62; Cutler, 1995; Digerfeldt et al., 2007). Walking on wet lake marl is almost impossible because of the slippery surface and tendency to sink deeply into the sediment. Some lakeside settlements were placed in areas with no standing water and as far as we know on an already hardened surface (Jacomet, 1985; Ismail-Meyer, 2014). The platforms, which are poor in nutrient matter, were often almost vegetation-free, but longer regression phases permitted pioneer vegetation to grow there (Jacomet, 1985; Monnier et al., 1991; Jacomet and Brombacher, 2005).

Micromorphological analyses of lake marl offer clues to the height of the lake level before, during, and after a settlement phase on the basis of layering, sand enrichments, and preservation of mollusk shells. The installation of a settlement in a sufficiently dry area generally led to compaction of the lake marl and enrichment of charcoal, wood, and bark chips due to house-building activities (Figures 2 and 3; Ismail-Meyer and Rentzel, 2004; Jacomet et al., 2004; Ismail-Meyer et al., 2013). These remains of scattered wood and bark chips may have helped to make these areas more easily accessible (Jacomet et al., 2004).

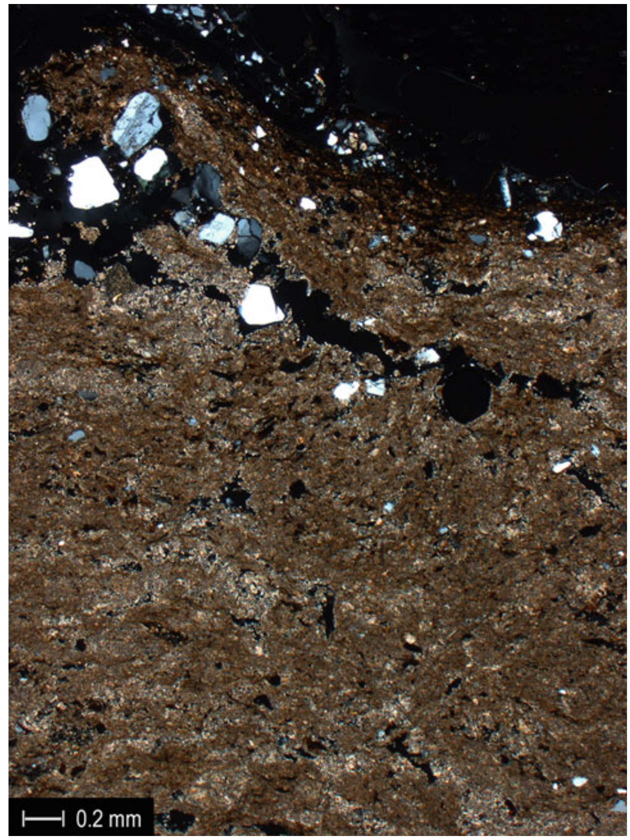
Hydrology

Hydrology in natural wetlands

Under waterlogged conditions, organic matter can accumulate over time at the surface by a sedentary process



Paludal Settings (Wetland Archaeology), Figure 2 Lake Luokesa, Lithuania, photomicrograph of a thin section in plane-polarized light (PPL): Limnic carbonate (lake marl) overlain by an archaeological deposit. The sediment of the lower part has a heterogeneous aspect due to dense gray lake marl peds enriched with some brown organic detritus. It is supposed that limnic influence led to mixing of the lake marl peds with organic matter. In the uppermost third of the picture, some transparent quartz sand grains are covered by compact organic remains, leaves (*arrow*), and a piece of charcoal at the top, the whole representing an activity surface with possible trampling features.



Paludal Settings (Wetland Archaeology), Figure 3 Same section as Figure 2, with crossed polarizers (XPL): The carbonate marl is *pale*, organic remains appear *dark brown to black*, and quartz grains *white and bluish gray*.

because anaerobic conditions reduce decay rates (French, 2003, 17; Charman, 2009, 542). The organic matter derives mainly from locally growing mosses, herbaceous material, and leaf litter (Mitsch and Gosselink, 2007, 168; Dodds and Whiles, 2010, 95ff; Menotti, 2012, 11). In natural peatlands, the water table is determined by the balance between inputs from precipitation and surface inflow and losses through evaporation and transpiration (evapotranspiration) and seepage (van der Valk, 2006, 25; Mitsch and Gosselink, 2007, 107; Digerfeldt et al., 2007; Keddy, 2010, 66).

One of the most important characteristics of peatlands is a high groundwater table, which lies at, or near, the surface (van der Valk, 2006; Keddy, 2010, 22; Armstrong, 2010, 30). In the temperate zone, groundwater fluctuates seasonally from a high in winter to a low in summer due to changing transpiration rates (Middleton, 1999, 9; Corfield, 2007, 144; Baker et al., 2009, 141). According to Holden and Burt (2003, 91), in a natural environment, the water table does not drop more than 5 cm below the peat surface. In raised bogs, the water table is naturally raised above the normal height because of capillary conduction by the growing plants adapted to waterlogged conditions, such as sphagnum mosses (Armstrong, 2010, 31). It seems that organic accumulations can also act as a “sponge” and raise the local water table so that the fringe of capillary water rises above it (Kenward and Hall, 2000, 522). The hydraulic conductivity (capacity of soils to retain water) is generally low in peats, meaning that they have strong water retention and remain wet for lengthy durations of time (Corfield, 2007, 147; Charman, 2009, 541).

Peats reveal an internal succession: in the upper, active zone called the *acrotelm*, fresh plant material is added at the surface. Here, the organic matter is loosely packed and loses more water due to evaporation (higher hydraulic conductivity). Fungal and bacterial growth leads to rapid decomposition of organic matter. The thickness of the acrotelm layer ranges from a few mm up to 75 cm, depending on the local hydrology (Mitsch and Gosselink, 2007, 173; Lindsay, 2010, 6). Water can move quickly horizontally and vertically (Dierssen, 2003, 204; Baker et al., 2009, 133; Charman, 2009, 542f.). The deeper, less active zone, the *catotelm*, lies below the local water table, where water moves slowly through the more compacted matter. Due to the constantly waterlogged conditions, there is minimal decay by anaerobic bacteria (Dierssen, 2003, 204; Baker et al., 2009, 133f.; Charman, 2009, 542f.).

With a vegetation cover, evapotranspiration rates are higher, but a dense covering of dead vegetation prevents sunlight from reaching the soil surface and lowers the evaporation rates (Baker et al., 2009, 139).

Wetlands lying adjacent to a lake or river may be termed "surface water slope wetlands". They are fed mostly by precipitation, surface flow, and flooding from the lake or river (Mitsch and Gosselink, 2007, 136), and they form only where the topography of the lake margin is flat (Jacomet et al., 2004; Baker et al., 2009, 125).

Hydrology in lakeside settlements

Lakeside settlements were constructed at the interface between limnic and terrestrial environments (Menotti, 2012, 13f.). They may be compared to "surface water slope wetlands," fed mainly by surface flow and lake inundations. The presence of large amounts of organic accumulations, often showing neither limnic nor terrestrial signs, demonstrates the complexity of the hydrological balance in lakeside settlements (Jacomet, 1985, 385; Ismail-Meyer and Rentzel, 2004). There is evidence that the acrotelm-catotelm model observed in natural peats also fits anthropogenic accumulations in several ways. Following the hydrology in peatlands, it is assumed that organic accumulations in pile-dwelling sites have significant water retention, which is due to a "sponge" effect. Without a dense active plant covering over the organic layers (there is some evidence for locally growing plants: Jacomet et al., 2004; Jacomet and Brombacher, 2005), evapotranspiration must have been rather low. The accumulations must have been water saturated over most of the time in order to maintain conditions that allowed such excellent preservation of organic matter (Kenward and Hall, 2004; Jacomet et al., 2004).

Organic accumulation

Organic accumulation in natural wetlands

Plant parts transported into lake bodies accumulate at the sediment-water interface and in shallow water (Gastaldo and Demko, 2011, 254f.), usually in areas with minimal wave action or flowing water (Keddy, 2010, 22f.). Wetlands develop only in areas that possess water-saturated surfaces during the major part of their existence in time and where the rate of accumulation exceeds that of organic-matter decay (French, 2003, 17; Mitsch and Gosselink, 2007, 156; Charman, 2009, 542f.; Gastaldo and Demko, 2011, 256).

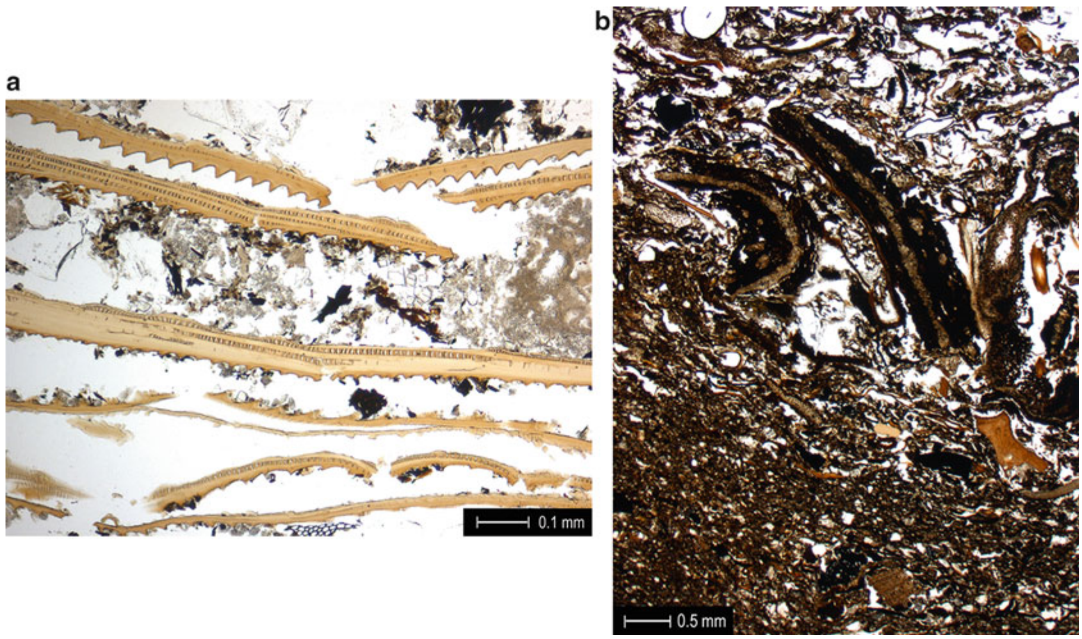
The fibrous composition of peats provides a strong structure and very high moisture content because of high capillarity. In the acrotelm, fresh plant material from mosses, sedges, and grasses is added at the surface, where most of the decay takes place (Charman, 2009, 541ff.). The residence time of the organic remains in the acrotelm may be about 100 years before they pass into the waterlogged catotelm. This implies a very slow growth rate of 0.5–2 mm per year (Lindsay, 2010, 78; Keddy, 2010, 193). Bones found in peat bogs are tanned by humic acids and often demineralized, which can be attributed to the lowering of pH or the presence of sphagnum moss, which decalcifies bone (as it does with "bog bodies"). Framboidal pyrite may form within cracks and pores in bones due to the colonization by sulfate-reducing bacteria (Turner-Walker and Mays, 2008).

Anthropogenic accumulation

In archaeological contexts, organic accumulations in wet environments resemble natural peats, but they are often of pure anthropogenic origin (Kenward and Hall, 2008, 585). Natural peat growth can also occur in settled areas, but this should be confirmed by botanical analyses (e.g., Maier, 2011).

Anthropogenic accumulations of organic matter consist mainly of wood and bark chips, leaves, twigs, mosses, agricultural remains, dung, bones, charcoal, ashes, sand, and loam (Figure 4a, b). Due to their morphology, wood, bark, foliage leaves, needles, mosses, and some seeds may be identifiable (see Schoch et al., 2004; Ismail-Meyer, 2016). The structure and shape of excrements sometimes allow the identification of the animal (Brönnimann et al., 2016a, 2016b). Bones of large animals, fish, and amphibians may also accumulate within the organic sediments; often, they still show their histological features (Huisman et al., 2009). Ashes can be distinguished due to their internal structure (Braadbaart et al., 2012). The accumulations are the result of different activities in the settled area – house building, food preparation, disposal of waste, handicrafts, animal husbandry, gathering, hunting, and fishing (Ismail-Meyer and Rentzel, 2004; Jacomet et al., 2004).

The well-preserved cultural layers show horizontally oriented remains of different sizes in a small-scale patchwork. This arrangement is the result of complex interaction between erosive and accumulative processes and various human and animal activities (Jacomet et al., 2004). The organic remains are usually very well preserved under waterlogged conditions. The presence of chlorophyll in some cases indicates a very fast sealing and burial, perhaps in less than 3 days or even within hours (Meyers and Ishiwatari, 1993, 886; Jacomet et al., 2004; Kenward and Hall, 2004, 8). Generally, such preservation is possible only because of a rapid accumulation rate (e.g., several centimeters every year) that occurred in the central



Paludal Settings (Wetland Archaeology), Figure 4 (**a**) Zug-Riedmatt, photomicrograph in plane-polarized light (PPL): Several well-oriented fish remains (gills and scales) in different stages of preservation (well preserved at the *top*) and showing layers of micropores (possibly due to chemical dissolution) in the rest of the picture. (**b**) Zug-Riedmatt, photomicrograph in plane-polarized light (PPL): Highly organic anthropogenic deposit and in the lower part, a laminated layer composed of highly fragmented organic matter (detritus). The upper, more porous part contains bigger organic remains with many dark brown bark fragments. An example of an outdoor area within a water-saturated, paludal depositional environment.

part of a village or in protected, swampy areas beneath raised houses (Jacomet et al., 2004; Ismail-Meyer and Rentzel, 2004; Ismail-Meyer et al., 2013). Such features demonstrate that, compared to the annual growth rate of a natural peat, lakeside settlements demonstrate a very different kind of accumulation process. Signs of decay in such waterlogged accumulations occur and can usually be attributed to anaerobic bacteria. This includes degradation of wood (Huisman and Klaassen, 2009). Bones may show a dark staining of the surface due to humic acids, precipitation of framboidal pyrite due to sulfate-reducing bacteria, tunneling caused by cyanobacteria, and loss of collagen, the major organic component of bones (Bocherens et al., 1997; Turner-Walker and Mays, 2008, Huisman et al., 2009).

Flooding events

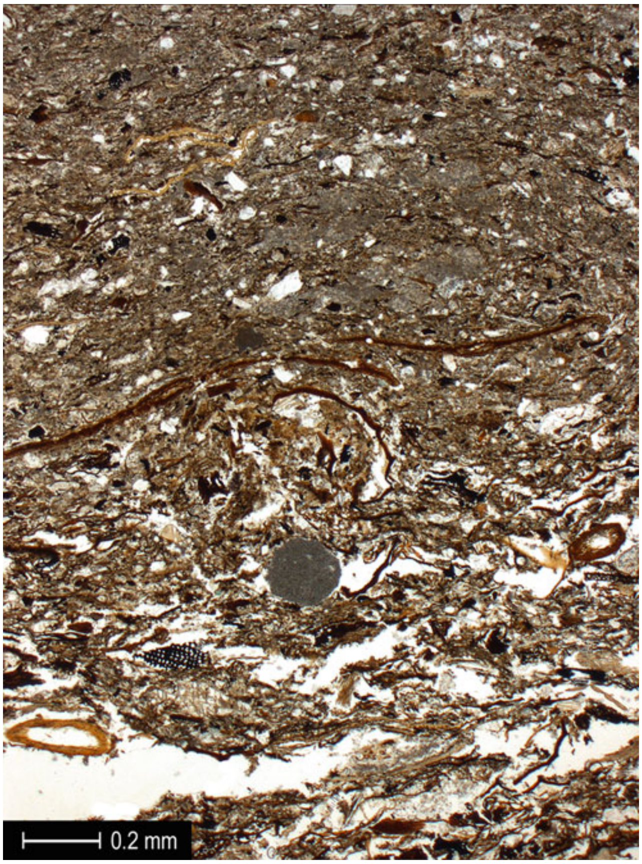
Lake-flooding events in natural peatlands

Flooding in wetland areas represents a natural event, and it occurs either seasonally or interannually. In the temperate zone, floods are produced each spring by the rapid melting of the precipitation accumulation of an entire winter, especially in mountainous areas (Middleton, 1999, 9; Mitsch and Gosselink, 2007, 132; Baker et al., 2009, 127; Keddy, 2010, 44). Therefore, large lakes depending on an alpine water regime may show yearly fluctuations in the water table of a few meters, while in small lakes and ponds, such fluctuations are rather weak (Keddy, 2010, 77). Long-term fluctuations in rainfall due to climate change may cause dramatic changes in the shoreline (Keddy, 2010, 44, 59).

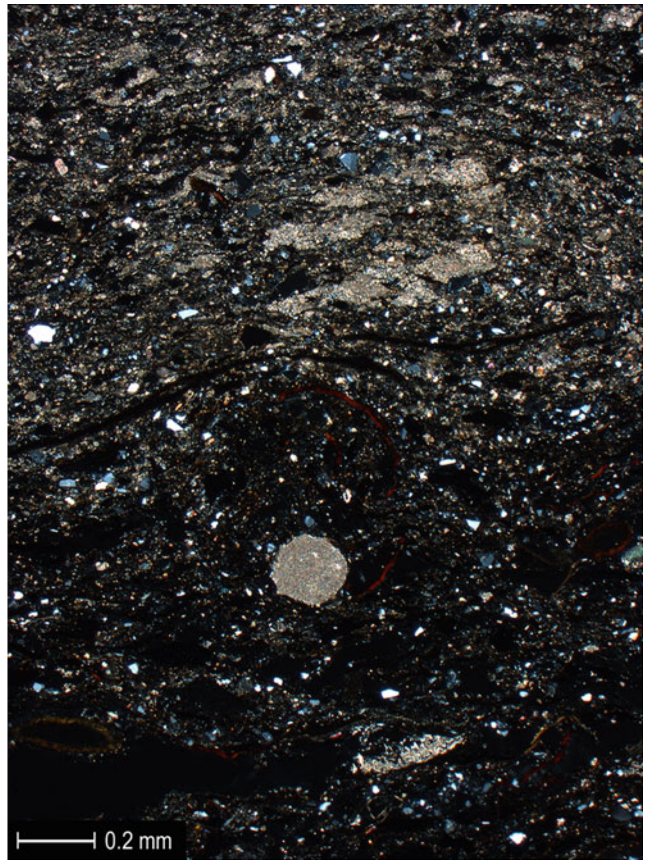
The major effects of flooding are erosion and deposition (Turnbaugh, 1978, 595). During flooding, wetland areas may be exposed to wave action, which imposes complex effects on littoral areas. The amount of wave energy impacting a shoreline increases with distance to the opposite shore and with the number of directions from which waves can arrive (Keddy, 2010, 121). With high levels of exposure to waves, fine particles and biomass tend to be removed, and sorted, coarser substrates such as sand and gravel are left behind (Magny, 2004; Digerfeldt et al., 2007; Keddy, 2010, 121). Resuspension of sedimented organic matter can be considerable, but it is usually more frequent in large rather than in small lakes (Meyers and Ishiwatari, 1993, 868).

Lake flooding in lakeside settlements

Flooding events may be frequent in lakeside settlements of the Circum-Alpine region, and they are also mainly linked to the spring flood. Climatic changes in late prehistoric times led to more permanent inundation of shore areas and may have caused the abandonment of a number of lakeside settlements (Menotti, 2001, 2004). High lake levels led to flooding, erosion, and/or redeposition of remains (Figures 5 and 6).



Paludal Settings (Wetland Archaeology), Figure 5 Zug-Riedmatt, photomicrograph in plane-polarized light (PPL): In the lower half of the picture appears an organic cultural layer, truncated and overlain by limnic sediments with gray lake marl peds mixed with some eroded organic remains. Example of a flooding event after an occupation phase in a paludal environment.



Paludal Settings (Wetland Archaeology), Figure 6 Same section as Figure 5, with crossed polarizers (XPL): In the upper half of the picture, the limnic carbonates appear gray, and the layered organic remains are black.

Micromorphological analyses show that organic layers may be eroded by water movements coming from the lake. Erosion boundaries are difficult to detect, even in a thin section. Often, parts from the flooded organic accumulations are suspended and redeposited together with limnic sediments. Such layers consist of homogenous limnic carbonates containing mollusk shells, algal remains, and frequently large amounts of highly fragmented organic detritus (see below). It is also possible to observe organic layers with very rare algal remains, diatoms, sponge needles, and mollusk shells which seem to be in situ, but they must have been in suspension for a short period without any visible effect of wave action (Jacomet et al., 2004). It is obvious that palisades, house constructions, and on-site vegetation, such as reeds, have influenced the water movement through a lakeside settlement by breaking down wave energy.

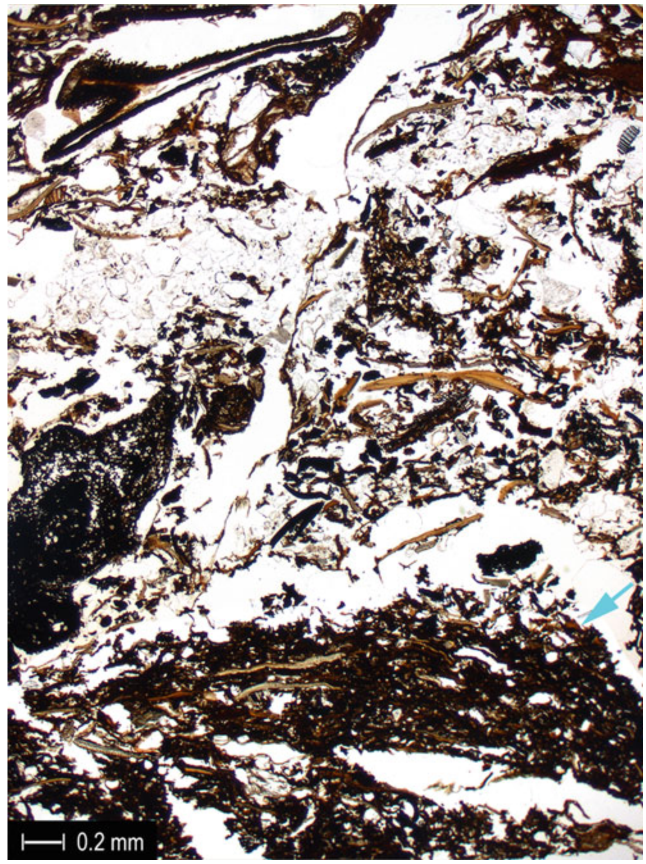
Deposition of reworked lake marl, which shows no signs of laminations, may be the result of a single storm event. During longer phases of transgressions, laminated lake marl precipitates in situ (Digerfeldt et al., 2007).

Flooding due to runoff in natural peatlands

Erosion by water also occurs during spring through runoff from the upper slopes caused by rains and snowmelt, especially when the vegetation cover has been disturbed by forest clearance and agriculture (Turnbaugh, 1978, 606; French, 2003, 17, 22; Goldberg and Macphail, 2006; Keddy, 2010, 193; Zolitschka et al., 2010, 82). Infiltration into unsaturated peat (acrotelm) is fast. When a peat is already completely water saturated, surface flow occurs and may affect a large area of a floodplain (Baker et al., 2009, 126). Therefore, surface runoff can be strong, occurring even on gently sloping areas (Turnbaugh, 1978, 597). About 80 % of surface water flows through the acrotelm, and 98 % of the runoff occurs in the topmost 3 cm (Holden and Burt, 2003, 91; Baker et al., 2009, 122). Runoff follows immediately after rainfall or spring thaw. Even small amounts of precipitation produce long-lasting surface flow, and just 1 day of heavy rain will cause a sharp rise in the water table (Holden and Burt, 2003, 91f.; Mitsch and Gosselink, 2007, 126; Lindsay, 2010, 129). The waterlogged catotelm, where water moves very slowly, is usually not affected by flood events (van der Valk, 2006, 25, 150; Charman, 2009, 543f.; Lindsay, 2010, 128).

Wetlands that are characterized by inflows from a wider catchment receive allochthonous sediment inflows. The rate of sediment brought in depends on the magnitude and frequency of precipitation (Baker et al., 2009, 153). The main sediment charge arrives during the short, intensive period of water discharge in spring (Mitsch and Gosselink, 2007, 133). But it is also known that forest clearing and human land use lead to destabilization of slopes. The consequences are soil erosion, increased runoff, and higher levels of minerogenic sediment transfer from the catchment area into the lakes (Dierssen, 2003, 199; French, 2003, 24; Digerfeldt et al., 2007; Baker et al., 2009, 153; Zolitschka et al., 2010, 82; Menotti, 2012, 256). Except under very low flow velocities, silts and sands are quite easily detached from the soil mass and redeposited (French, 2003, 24).

Vegetation, such as reeds and bushes, slows down surface flow, so that in summer the flow resistance is high, and in winter the resistance declines. Seasonal cycles of plant growth have an impact on the timing of sediment mobilization (Baker et al., 2009, 136). A plant cover, roots, and leaf litter at the surface may also protect wetlands from erosion (Turnbaugh, 1978, 597; Baker et al., 2009, 158). Burial by successive layers of sediment leads to compaction and consolidation, so that only a little of the sediment is resuspended (Baker et al., 2009, 158).



Paludal Settings (Wetland Archaeology), Figure 7 Lake Luokesa, photomicrograph of a thin section in plane-polarized light (PPL): Dense organic crust (*arrow*) of decomposed organic matter, probably due to desiccation. A sandy layer, possibly an inwash from the hinterland, covered the organic layer.

Flooding due to runoff in lakeside settlements

Micromorphological analyses show that flooding from the hinterland also results in erosion and inwash by surface flow of well-sorted and graded sands from the catchment area (Figures 7 and 8). Due to surface water outflow into the lake, highly fragmented organic matter (detritus; see below) may be lost from the settlement site (Mitsch and Gosselink, 2007, 158f.). Unsorted layers rich in sand can also be anthropogenic in origin due to (1) loss of organic matter, (2) alteration of cultural layers, or (3) disaggregation of construction material such as loam walls.

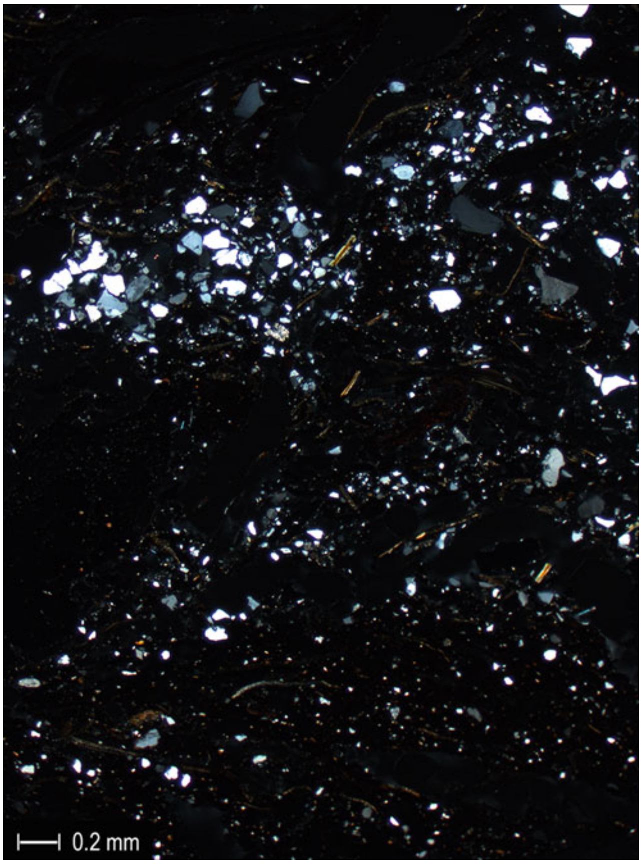
Sequences of alternating organic layers and sandy inwash are interpreted as seasonal deposits (see below). Microstratigraphic observations have documented that flooding and/or reworking of organic layers does not involve the entire anthropogenic sequence – as such a result would yield homogeneous sediments without laminations – but only the uppermost part of the sequence is affected (Jacomet et al., 2004). This situation may be explained by the acrotelm-catotelm model, indicating that surface flow occurs mainly in the uppermost part, while the denser, waterlogged catotelm is not affected. Obviously, it is impossible to know how much of the sediment was previously removed by erosion, but it was probably not more than a few cm per flooding event. Generally, the lakeward parts of sites were more affected by lake flooding, while the areas toward the landward side were influenced instead by surface runoff (Jacomet, 1985; Jacomet et al., 2004; Ismail-Meyer and Rentzel, 2004; Ismail-Meyer et al., 2013). House constructions, palisades and on-site vegetation may have slowed water movement through the site.

Lowering of the water table

The preservation of organic remains in wetlands is connected to the height of the lake level or the groundwater table. This section will explain how and why organic matter decays in wetlands and waterlogged archaeological sites.

Lowering of the water table in natural wetlands

During the summer, the water table in wetlands may drop due to higher evaporation rates, causing desiccation and decomposition of organic matter (Keddy, 2010, 66;



Paludal Settings (Wetland Archaeology), Figure 8 Same section as Figure 7, with crossed polarizers (XPL): The quartz grains from the sandy inwash are visible in *white and bluish colors* in the upper half of the picture.

Gastaldo and Demko, 2011, 255). Decay of plant remains occurs in approximately three stages. First, plant cell contents and food stores of seeds disappear through fermentation; second, plant cell walls and insect remains decay; and third, most remaining organic matter disintegrates, and only the most resistant plant residues survive and can be recovered, such as cuticles, lignin-containing cells from wood and bark, and phytoliths (plant silica) (Kenward and Hall, 2000, 520, 2004, 5; Gastaldo and Demko, 2011, 255). The so-called detritus or particulate organic matter – also a result of organic decay in wetlands – measures between 0.45 µm and 1 mm in size. In wetlands, oxygenation, desiccation, and bacterial and fungal activity (without arthropods and other typical soil animals) lead to detritus formation. Dried-out peats are reduced to a loose detritus powder as a result of the combined effect of sun and wind – without further physical abrasion (Mitsch and Gosselink, 2007, 157; Lindsay, 2010, 85; Gastaldo and Demko, 2011, 255). Detritus appears after the dry period due to peat erosion, and it accumulates at the surface during a short period of stability. Due to precipitation, it enters into streams mainly between September and the end of November (Blazejewski et al., 2005, 1323f.; Lindsay, 2010, 110; Marxsen and Wagner, 2011, 77; Gastaldo and Demko, 2011, 255).

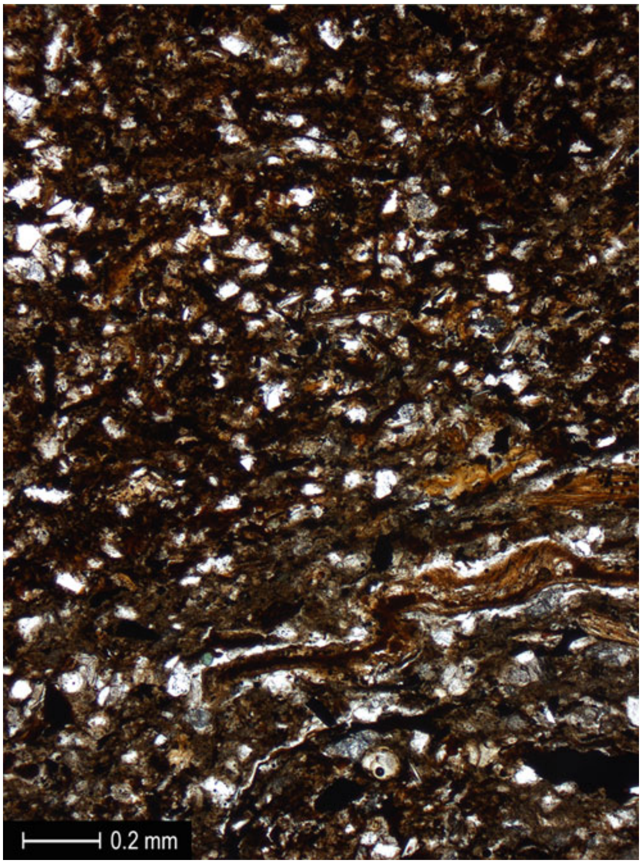
Fluctuations in the groundwater table also introduce oxygenated waters leading to biochemical processes that play a part in reducing plant parts (Gastaldo and Demko, 2011, 255). For instance, the redox potential, or Eh (the tendency of oxidation or reduction), is probably one of the most significant variables influencing the rate of organic degradation (Retallack, 1984). Oxidation occurs mainly in aerobic conditions and leads to decomposition and humification (Kenward and Hall, 2004, 6f.). When oxygen-rich water is introduced into peats, it normally takes only a few hours or days until the oxygen in the flooded layers is depleted by bacterial and fungal activity (Mitsch and Gosselink, 2007, 173). Under reducing conditions, anaerobic bacteria are the primary active microorganisms that are responsible for organic decay (Lillie and Smith, 2009, 17, 21). Rotting of wood has been observed due to fungi (white and red rot; Schweingruber, 1982; Huisman and Klaassen, 2009). Faunal activity in wetlands also leads to a reduction in peat volume and the development of humus, such as mull or moder (Babel, 1975; Malterer et al., 1992). Peats possess about 80 % pore space, which is filled with water in saturated areas (Mitsch and Gosselink, 2007, 166). Lowering of the water table in a natural peat leads to rapid subsidence of the surface because the porosity collapses. The increasing weight of the drier sediments above affects the peat column beneath. Every centimeter of drawdown in the water table results in an increased load of 10 kg m^{-2} (Lindsay, 2010, 123). Drying out and alteration of bogs, the so-called peat ripening, can also lead to compact sediment showing cracking and prismatic or granular microstructure (Malterer et al., 1992; Stolt and Lindbo, 2010, 385; Lindsay, 2010, 135). Dissolution of organic matter in acidic waters, probably combined with desiccation, may cause a transformation into amorphous, dark brown, jellylike concentrations, called dopplerite (Stolt and Lindbo, 2010, 385). As a consequence of syn- and postsedimentary dissolution phenomena, gelatinous dopplerite may be formed, but needs a phase of drying out to become insoluble (Wetzel 2001, 631). Another result of low water table in peats is the formation of amorphous organic matter (AOM) (Comont et al., 2006).

Bones from desiccated peat bogs show signs of demineralization, shrinkage, and cracking due to drying and may contain gypsum crystals (see below; Turner-Walker and Mays, 2008).

In wetlands, a slow process called terrestrialization may take place whereby wetlands become shallower and shallower with time; eventually, the wetland turns into dry land (van der Valk, 2006, 98).

Lowering of the water table in lakeside settlements

For archaeological remains, the main phase of decay generally occurs before, during, and for a short period, after



Paludal Settings (Wetland Archaeology), Figure 9 Stansstad-Kehrsiten, Switzerland, photomicrograph of a thin section in plane-polarized light (PPL): Compact organic detritus with fine-grained sand – the result of an alteration (desiccation) of the organic matter and runoff from the hinterland.

deposition. Soon after burial, ground conditions typically become more or less stable (Kenward and Hall, 2000, 522). Later episodes of decay due to dewatering (drainage or lake level corrections) lead to uniformly and poorly preserved remains within the near surface deposits (see below).

Micromorphological signs of dropping groundwater level, desiccation, and decay include a very dark brown color of the organic matter, a higher rate of compaction, fragmentation to the size of detritus, and the formation of dopplerite, organic crust, and AOM (Figure 7, see below). Mesofaunal droppings in decomposing wood and bark, fungal spores, and hyphae occur, but usually there are no signs of arthropod or other soil animal activity (Pawluk, 1987; Stolt and Lindbo, 2010).

Lowering of the water table in lakeside settlements allows the entry of air and rainwater rich in oxygen. Repeated wetting and drying cycles produce fragmentation of the organic remains and the development of detritus (Figure 9). Desiccation also leads to the collapse of porosity and, consequently, surface subsidence (Lindsay, 2010, 123). The formation of organic crusts, i.e., compact, layered, organic aggregates, may be connected to such processes, as seen in peat environments (Comont et al., 2006). Fungal and bacterial activity may also reduce plant parts to detritus (Gastaldo and Demko, 2011, 255). Wood may be heavily attacked by fungi, such as white and red rot (Schweingruber, 1982; Huisman and Klaassen, 2009). After hiatuses, e.g., due to abandonment of a site, organic layers showing strong signs of decay and mesofaunal droppings, of e.g. springtails (Collembola) and/or pot worms (Enchytraeidae) may be observed (Ismail-Meyer, 2014). Due to weathering, sediment can become more minerogeneous. The presence of dopplerite and amorphous organic matter (AOM) seems to indicate drier parts of lakeside settlements or may be formed during acidic phases, but it may also have been precipitated as a result of modern drainage in wetland areas (see also below). Animal bones may show diverse signs of degradation, such as loss of birefringence due to loss of collagen (Gilbert, 1989, 59), tunneling as a result of aerobic bacteria and fungi (microfocal destruction or bioerosion), cracking, and signs of dissolution due to chemical weathering. Gypsum crystals may also occur in cracks and pores as a result of the reaction of dissolved calcium with sulfate released by pyrite decay (Bocherens et al., 1997; Jans et al., 2004; Turner-Walker and Mays, 2008; Huisman et al., 2009).

Heterogeneous conservation of the organic remains indicates synsedimentary alteration (and inherited elements) if conditions have been stable through time. If signs of decay appear confined to single layers of lakeside settlements, followed by well-preserved ones, a possible interpretation is that these altered levels reveal seasonal drying, with decay having occurred pre- or immediately post-burial (see below; Kenward and Hall, 2000, 521; Ismail-Meyer, 2014).

Postdepositional processes in natural wetlands and lakeside settlements

After burial, only very slow decay and almost no post-burial alteration (diagenesis) occur, as long as the ground conditions persist (Kenward and Hall, 2000, 522, 2004, 6f.). Under permanent waterlogged conditions, organic remains from pile-dwelling sites may show, more or less, the same preservation upon excavation as existed shortly after their burial. But the recent growth of reed belts around lakes could have major effects on the arrangement of the remains, leading to mixing of several layers (Ismail-Meyer and Rentzel, 2004; Jacomet et al., 2004).

Human activities such as agriculture, forestry, stream canalization, dam and dike construction, mining, groundwater extraction, and the creation of water pollution have major impacts on wetlands (Middleton, 1999, 56ff.; Mitsch and Gosselink, 2007, 289), which are disappearing very fast (Menotti, 2012, 226). Modern drainage leads to peat loss due to consolidation, compression, oxidation, and pedogenesis (Lindsay, 2010, 124; Gastaldo and Demko, 2011, 261), and as an example, the drainage of a freshwater lake in England led to the loss of 4 m of peat volume (Lindsay, 2010, 123ff.). Archaeological wetland sites experience the same effects as natural wetlands due to drainage, and such changes can be seen in the landward part of Arbon-Bleiche 3 (Jacomet et al., 2004).

When the natural wetland environment vanishes, our cultural heritage is lost, too. Maintaining the natural environment by stabilizing the water table, controlling water quality, and taking anti-erosion measures can protect many wetlands and archaeological wetland sites from post-burial decomposition (Cole, 1995, 31ff.; Mitsch and Gosselink, 2007, 305; Menotti, 2012, 19, 226). Thanks to the Ramsar Convention, an international contract originally begun in Ramsar (Iran) in the early 1970s, the protection of wetland habitats around the world has been promoted (Mitsch and Gosselink, 2007, 519; Ramsar Convention). The interest group "Preserving Archaeological Remains In Situ" (PARIS) regularly organizes international conferences about in situ preservation. Discussion of in situ protection for wetland sites can be found in Cole (1995), Vernimmen (2002), Lillie (2007), Lillie and Smith (2009), and Kenward and Hall (2008).

Excellent preservation in lakeside settlements

Organic matter in wetlands often shows excellent preservation because of waterlogged, anoxic conditions (Figure 4a, b; Kenward and Hall, 2000, 521), and the best preservation of organic remains occurs in areas that lie between the limnic and terrestrial environments. On very flat and protected lakeshores, plant remains may accumulate, constantly soaking up humidity from the groundwater as happens in natural peatlands (Jacomet et al., 2004; Gastaldo and Demko, 2011, 254f.).

Under waterlogged, anoxic conditions, often only the first stage of organic decay occurs, i.e., loss of cell content and food stores of seeds before, during, or shortly after deposition (Kenward and Hall, 2000, 520–522, 2004, 5). Rapid sealing of the remains under a high sedimentation rate during the growing season – possibly enhanced by compaction caused by human and animal trampling – leads to excellent preservation. In many lakeside settlements, green leaf tissue is still preserved, cattle and sheep/goat dung has kept its original shape (and smell), and dung-dwelling insects are practically absent (Kenward and Hall, 2004, 8; Jacomet et al., 2004; Ismail-Meyer et al., 2013). The bones often show very good preservation, and even highly fragile fish gills and scales can be recognized (Figure 4a). Soon after burial, ground conditions become more or less stable because of the quickly depleted oxygen resulting from fungal and bacterial activities (French, 2003, 17; van der Valk, 2006, 19; Kenward and Hall, 2008, 585; Lillie and Smith, 2009, 11; Keddy, 2010, 22; Menotti, 2012, 228f.). This is probably the reason why there are almost no signs of fungi in waterlogged areas (van der Valk, 2006, 40). Waterlogged organic material may account for 75–90 % of all the material recorded (Lillie and Smith, 2009, 9). If such conditions that are conducive to long-term preservation are not stable over time, remains usually decay quickly and completely (Kenward and Hall, 2000, 522).

Trampling effects on waterlogged organic accumulations

In settled, terrestrial areas, occupation activities generally produce compacted surfaces. In wetland sites, the most clearly visible effect of trampling can be seen in the minerogenic lake marl sediments at the base of the anthropogenic accumulations and loam floors in houses (see, e.g., Rentzel et al., 2016). Highly organic accumulations seem not to preserve clear signs of trampling over a long period of time because they expand to their original shape like a sponge (Jacomet et al., 2004; Ismail-Meyer and Rentzel, 2004). Dense organic crusts are not the result of trampling, but refer to phases of decay (Figures 7 and 8; see above; Ismail-Meyer, 2014).

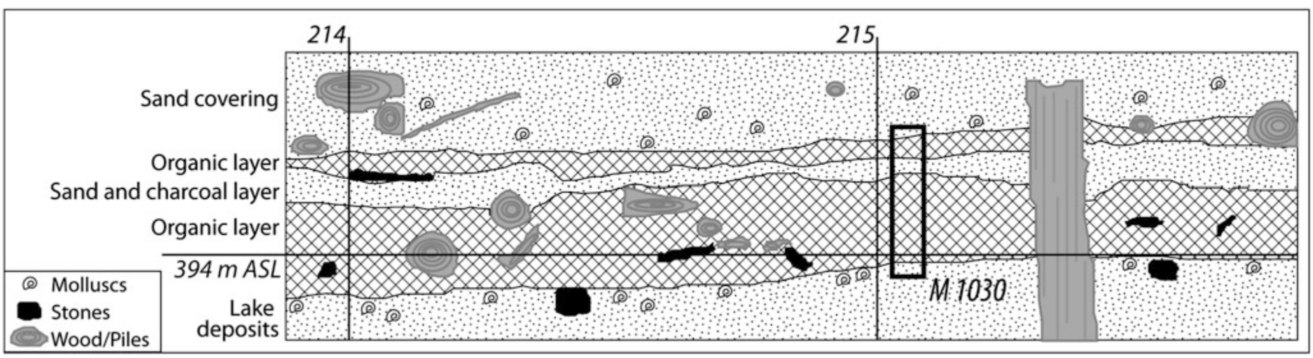
Seasonal processes

Many processes observed in lakeside settlements are linked to seasonal events. Micromorphological observations often show organic laminations (from a few millimeters up to several centimeters in thickness), which may confirm a decomposition and compaction of organic matter at the surface. Sometimes, they are covered by a tiny layer of well-sorted and graded sand, which shows a sharp lower boundary. In near-shoreline areas, the sandy layers can be replaced by lake marl layers containing substantial amounts of detritus and amorphous organic matter (Figure 9). These sequences may be the result of seasonally induced changes, as observed in Lake Luokesa, Arbon-Bleiche 3, and Stansstad-Kehrsiten. Multidisciplinary investigations have demonstrated that they can be interpreted as follows. During phases with high water tables, large amounts of fresh material accumulate in the settlements as a result of human (and animal) activities. A quick sealing by covering deposits under waterlogged conditions leads to extremely good preservation. During the hot season, the groundwater level can drop a few cm causing desiccation, as well as fungal, mite, and bacterial involvement. In spring, flooding and substantial surface flow can lead to erosion of the topmost layer (a maximum of a few cm) as well as deposition of sand from the catchment area. Sand inwash seems to occur especially during settlement phases which are associated with forest clearing and agricultural activities. Near the lake, flooding may occur at the same time, depositing lake marl with eroded detritus from the site (Ismail-Meyer, 2014).

Fire events

Fire events occur regularly in wetlands when the peat surface is sufficiently dry during seasonal or interannual dry

Paludal Settings (Wetland Archaeology), Figure 10 Arbon-Bleiche 3, Switzerland: Field view of the south profile through House 1. The laminated, gray lake and beach deposits are overlain by the dark brown cultural layer. Note also the effects of modern trampling of the water-saturated lake marl in the right foreground, leading to ductile deformation phenomena (By Amt für Archäologie Thurgau, www.archaeologie.tg.ch, D. Steiner).



Paludal Settings (Wetland Archaeology), Figure 11 Arbon-Bleiche 3: West profile through House 1 showing the sequence with two main organic cultural layers divided by a charcoal-rich sandy layer. The rectangle M1030 corresponds to the micromorphological block sample (see Figure 12) (Drawing by Amt für Archäologie Thurgau, www.archaeologie.tg.ch and K. Ismail-Meyer, modified from Ismail-Meyer et al., 2013).

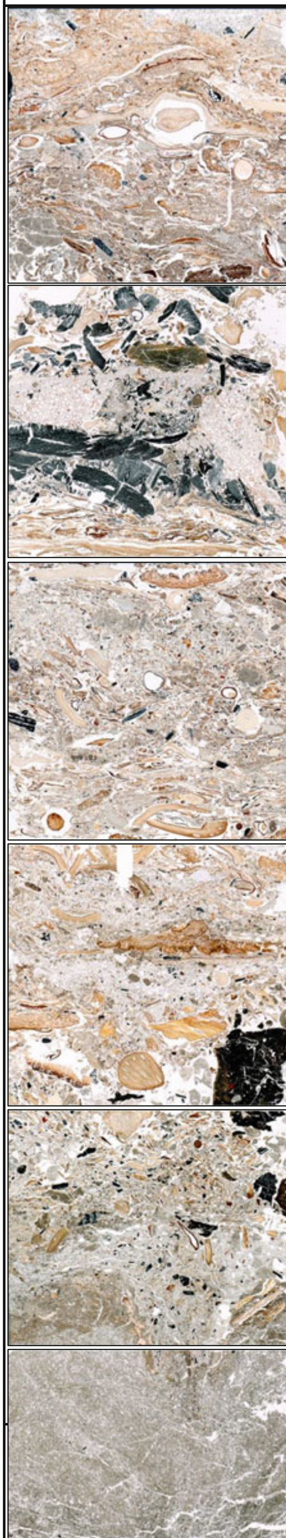
periods. The major sources of combustion are human activities and lightning (Middleton, 1999, 42ff.; van der Valk, 2006, 98; Lindsay, 2010, 215). Fire affects only the surface vegetation of a peat (Charman, 2009, 545) and produces much ash, which is easily removed by wind or washed away by rain. Fire is one of the most important causes for extensive peat erosion (Lindsay, 2010, 144, 248).

Lakeside settlements show signs of fire events that led to the destruction of single houses or even entire villages. The use of fire must have been dangerous, especially during the dry season. Thin sections reveal organic layers that bear indications of heat in the form of burnt plant material, ashes, and organic slags (melted phytoliths). Entire layers of charcoal occur, too, but these are rare, which must be due to the fact that charcoal is easily dislocated, fragmented by trampling, and removed by flooding events (Macphail et al., 2010, 47). For instance, a village destroyed by a fire will most likely be subsequently flooded, at which time substantial parts of the burned layers will be removed by wave action (Jacomet et al., 2004; Ismail-Meyer and Rentzel, 2004).

Case study: House 1 from Arbon-Bleiche 3

A micromorphological case study from Arbon-Bleiche 3 is presented here to illustrate the main processes in the

House 1: Scanned thin sections



Phase	Seasonal process	Microscopy	Dating
	Lake flooding	Erosive sandy layer with limnic aspect. Final flooding.	3370 cal BC
Stable	Winter?	Compact organic layer with altered and well preserved sheep/goat coprolites, mistletoe, and needles of white fir. Pollen indicating winter season.	
House in use	Dry Summer (low water table)	Compact organic layer with sandy clay matrix and detritus, fish scales, ashes, and altered sheep/goat coprolites.	
House in use	Dry Summer (low water table)	Compact organic layer with large amounts of matrix and detritus, altered sheep/goat coprolites, some seeds.	
House in use	Dry Summer (low water table)	Fine sand with clay and detritus, well preserved and altered bark remains.	
Renovation	Accumulation with high water table	Loose organic layer with charcoal, white fir needles, clay aggregates, twigs, no detritus.	
Renovation	Accumulation with high water table	Compact layer with charcoal, loam aggregates	3375 cal BC
	Hinterland spring flooding	Erosive sandy layer with well sorted sand and large amounts of poppy seeds. Disturbed.	
fire	?	Layer of large charcoal fragments with some fine sand.	
Raised house with goat/sheep staying sometimes beneath	Dry Summer (low water table)	Loose organic layer with wood, bark, white fir needles, moss, some detritus.	
Raised house with goat/sheep staying sometimes beneath	Accumulation with high water table	Organic layer with bark, white fir needles, wood, no detritus.	
Raised house with goat/sheep staying sometimes beneath	Hinterland spring flooding	Well sorted sandy layer.	
Raised house with goat/sheep staying sometimes beneath	Winter?	Compact layer with sand, gravel, twigs, some charcoal, and altered coprolites. Pollen indicating winter season.	
Raised house with goat/sheep staying sometimes beneath	Autumn?	Loose organic layer with many hazelnut shells, moss, twigs, leaves and loam aggregates, some sheep/goat coprolites. No detritus.	
Raised house with goat/sheep staying sometimes beneath	Accumulation with high water table	Compact layer with fine sand and clay matrix, some ashes and bark.	
Raised house with goat/sheep staying sometimes beneath	Hinterland spring flooding	Sandy layer.	
Raised house with goat/sheep staying sometimes beneath	Autumn?	Loose sand with bark, mollusk shells, organic remains, loam aggregates, twigs, mistletoe, fish bones, 1 ceramic fragment on the right side.	
Raised house with goat/sheep staying sometimes beneath	Lake flooding	Dense sandy layer with organic remains, charcoal, ashes, melted phytoliths, seeds (poppy and flax), mollusk shells, many bones, some with heat signs, loam, leaves, mosses, white fir needles, and one sheep/goat coprolite.	
Raised house with goat/sheep staying sometimes beneath	Lake flooding	Loose sandy layer with limnic elements, bark, charcoal, some seeds and bones, all reworked.	
Raised house with goat/sheep staying sometimes beneath	Dry Summer (low water table)	Compact lake marl (disturbed) with detritus, bark, weathered mollusk shells, bones, seeds, and leaves.	3384 cal BC
	Lake flooding	Sandy lake marl without layering, disturbed probably by a post. Many mollusk shells, some with signs of weathering. Precipitated in the littoral area, reworked by wave action, lake level flucuations occurred.	

Seasonal processes

- Lake flooding
- Hinterland spring flooding
- Accumulation with high water table
- Dry Summer (low water table)
- Autumn?
- Winter?

Paludal Settings (Wetland Archaeology), Figure 12 Arbon-Bleiche 3, House 1, sample M1030 (see location of sample in Figure 11): A compilation of scanned thin sections with a brief micromorphological description and a suggested interpretation of the archaeological layers, including possible seasonal processes (based also on botanical and palynological evidence).

formation of lakeside settlements. Arbon-Bleiche 3 is one of the most suitable examples for this purpose, as it is an extensively explored pile-dwelling site in the Circum-Alpine region that has received much interdisciplinary study (published by Jacomet et al., 2004; Menotti, 2012). This Neolithic site lies in northeastern Switzerland on the southern shore of Lake Constance, south of the town of Arbon. Today, the site lies inland compared to its original setting, which was located directly on the shore of a protected bay. The settlement was built in 3384 BC and was inhabited until 3370 BC (all dates coming from dendrochronology). This period falls in the middle of a cold phase (Piora 2) that experienced generally high lake levels. The site was constructed during a brief favorable climatic phase, when lake levels dropped for a short span of time (Haas and Magny, 2004).

The economy of Arbon-Bleiche 3 was based on the cultivation of plants, animal husbandry, and on gathering, hunting, and fishing. Animals were kept within the settlement during the winter months. The village was settled only once and for a relatively short time (15 years). Because the ground plans of the dwellings were clearly visible during the excavation, it was possible to take micromorphological samples from different functional areas of the site (e.g., within houses and alleys).

The basic stratigraphy of Arbon-Bleiche 3 consisted of sandy lake marl at the base, followed by a thin sandy beach layer that formed due to a regression of the lake before the settlement was installed (Figures 10 and 11). During the occupation, a 5–40-cm-thick archaeological stratum with several organic and sandy bands was deposited. The floors of the buildings were raised above ground level (Leuzinger, 2000). During the interval of settlement, depositional conditions must have been continually humid but without permanent standing water covering the area. The layers represent a complex puzzle of deposition and erosion. The entire anthropogenic deposit was covered by 2 m of sandy deposits almost "immediately," thereby promoting excellent preservation of the site until the moment of excavation.

Detailed geoarchaeological interpretation of the organic accumulations has enabled a reconstruction of the chronological biography of house number 1 (Figure 12). House 1 was the first to be constructed, dated to 3384 BC, and it was located in the middle of the settlement (and excavated area; Leuzinger, 2000). After its installation, a 10 cm sequence of organic layers was deposited, interrupted several times by sandy inwash from the hinterland. A local burned layer was then partially eroded by a further sandy inwash. The accumulation of a 7-cm-thick organic layer followed; it contained large amounts of sheep/goat coprolites and mistletoe.

This sequence can be interpreted as follows. The installation of House 1 led to compaction of the dry carbonate platform surface beneath it. During the time of settlement, organic layers accumulated but were repeatedly eroded and covered by thin sand layers, probably during spring floods and increased runoff. After 9 years of occupation, House 1 burned down and was subsequently flooded for a short period. A renovation in 3375 BC is demonstrated by dendrochronological investigations. Later, the roof collapsed and the house was abandoned. Botanical and palynological analyses confirm that the accumulation of the ovicaprid coprolites is an indication that the ruin was used as a stable for sheep and/or goats during the winter. In the spring of 3370 BC, the entire village burned down completely, and shortly after, the area was flooded by the lake (Haas and Magny, 2004; Ismail-Meyer and Rentzel, 2004, 76f.).

Summary

Geoarchaeological methods, including especially micromorphology, have become essential tools for the study of archaeological settlements in wetlands. In this contribution, special emphasis has been placed on micromorphological analyses of several prehistoric lakeside settlements in the Circum-Alpine region.

By comparing with actual processes ongoing in natural wetlands, the site formation processes of ancient lakeside settlements can be studied, and they are here summarized as accumulation of organic matter and its erosion, reworking, and decay, which is closely related to the height of the groundwater table and/or lake level.

Micromorphology, possibly combined with standard sedimentological investigations, shows great potential in reconstructing environments and site formation processes in wetland sites. Collaboration among different disciplines is fundamental, especially with archaeobotany, palynology, and dendrochronology, to obtain optimum results. In this way, it is possible to use the mosaic of different accumulations within a lakeside site to detect many human activities as well as natural processes, from flooding and erosion to dry periods associated with seasonal changes (Jacomet et al., 2004; Keddy, 2010, 131; Menotti, 2012, 19f.; Ismail-Meyer et al., 2013). The results of research obtained so far in this field have been remarkable, but there is much potential for significant applications of geoarchaeological methods to wetland archaeology in the future.

Bibliography

Armstrong, K., 2010. *Archaeological Geophysical Prospection in Peatland Environments*. Doctoral dissertation, Bournemouth University. http://eprints.bournemouth.ac.uk/16238/

Babel, U., 1975. Micromorphology in soil organic matter. In Giese-king, J. E. (ed.), *Soil Components*. New York: Springer. Organic Components, Vol. 1, pp. 369–473.

Babel, U., 1985. Basic organic components. In Bullock, P., Fedoroff, N., Jongerius, A., Stoops, G., Tursina, T., and Babel, U. (eds.), *Handbook for Soil Thin Section Description*. Wolverhampton: Waine Research, pp. 74–87.

Baker, C., Thompson, J. R., and Simpson, M., 2009. Hydrological dynamics I: surface waters, flood and sediment dynamics. In Maltby, E., and Barker, T. (eds.), *The Wetlands Handbook*. Oxford: Wiley-Blackwell, pp. 120–168.

Blazejewski, G. A., Stolt, M. H., Gold, A. J., and Groffman, P. M., 2005. Macro- and micromorphology of subsurface carbon in riparian zone soils. *Soil Science Society of America Journal*, **69**(4), 1320–1329.

Bleicher, N., 2014. Dendrochronological analyses of wood samples from a Late Bronze to early Iron Age site at Lake Luokesa, Lithuania. *Vegetation History and Archaeobotany*, **23**(4), 355–365.

Bocherens, H., Tresset, A., Wiedemann, F., Giligny, F., Lafage, F., Lanchon, Y., and Mariotti, A., 1997. Diagenetic evolution of mammal bones in two French Neolithic sites. *Bulletin de al Société Géologique de France*, **168**(5), 555–564.

Braadbaart, F., Poole, I., Huisman, H. D. J., and van Os, B., 2012. Fuel, fire and heat: an experimental approach to highlight the potential of studying ash and char remains from archaeological contexts. *Journal of Archaeological Science*, **39**(4), 836–847.

Braillard, L., Guélat, M., and Rentzel, P., 2004. Effects of bears on rockshelter sediments at Tanay Sur-les-Creux, southwestern Switzerland. *Geoarchaeology*, **19**(4), 343–367.

Brochier, J.-L., 1983. L'habitat lacustre préhistorique: Problèmes géologiques. *Archiv des Sciences de Genève*, **36**(2), 247–260.

Brochier, J.-L., and Bocquet, A., 1991. Histoire d'une inondation: La couche de craie B2 du site néolithique des Baigneurs à Charavines, Lac de Paladru, France. In *Archéologie et environnement des milieux aquatiques: Lacs, fleuves et tourbières du domaine alpin et de sa périphérie*. Actes du 116e congrès national des sociétés savantes, Chambéry, 1991. Paris: Comité des travaux historiques et scientifiques, pp. 62–82.

Brönnimann, D., Ismail-Meyer, K., Rentzel, Ph., Pümpin, Ch., and Lisa, L., 2016a. Excrements of herbivores. In Nicosia, C. and Stoops, G. (eds.), *Encyclopedia of Archaeological Soil and Sediment Micromorphology*. Chichester: Wiley-Blackwell.

Brönnimann, D., Pümpin, Ch., Ismail-Meyer, K., and Rentzel, Ph., 2016b. Excrements of ominvores and carnivores. In Nicosia, C. and Stoops, G. (eds.), *Encyclopedia of Archaeological Soil and Sediment Micromorphology*. Chichester: Wiley-Blackwell.

Burton, T. M., and Tiner, R. W., 2009. Ecology of wetlands. In Likens, G. E. (ed.), *Encyclopedia of Inland Waters*. Amsterdam: Elsevier, Vol. 3, pp. 507–515.

Charman, D. J., 2009. Peat and peatlands. In Likens, G. E. (ed.), *Encyclopedia of Inland Waters*. Amsterdam: Elsevier, Vol. 3, pp. 541–548.

Cole, B. (ed.), 1992. *The Wetland Revolution in Prehistory: Proceedings of a Conference Held by The Prehistoric Society and WARP at the University of Exeter, April 1991*. Exeter: Department of History and Archaeology University of Exeter. WARP Occasional Paper 6.

Cole, B., 1995. *Wetland Management: A Survey for English Heritage*. Exeter: WARP (Wetland Archaeology Research Project). WARP Occasional Paper 9.

Comont, L., Laggoun-Défarge, F., and Disnar, J.-R., 2006. Evolution of organic matter indicators in response to major environmental changes: the case of a formerly cut-over peat bog (Le Russey, Jura Mountains, France). *Organic Geochemistry*, **37**(12), 1736–1751.

Corfield, M., 2007. Wetland science. In Lillie, M., and Ellis, S. (eds.), *Wetland Archaeology and Environments: Regional Issues, Global Perspectives*. Oxford: Oxbow Books, pp. 143–155.

Cutler, A. H., 1995. Taphonomic implications of shell surface textures in Bahia la Choya, northern Gulf of California. *Palaeogeography Palaeoclimatology Palaeoecology*, **114** (2–4), 219–240.

Dierssen, K., 2003. Ecology and vegetation of peatlands. In Bauerochse, A., and Hassmann, H. (eds.), *Peatlands, Archaeological Sites, Archives of Nature, Nature Conservation, Wise Use: Proceedings of the Peatland Conference 2002 in Hannover, Germany*. Rahden: Verlag Marie Leidorf, pp. 196–209.

Digerfeldt, G., Sandgren, P., and Olsson, S., 2007. Reconstruction of Holocene lake-level changes in Lake Xinias, central Greece. *The Holocene*, **17**(3), 361–367.

Dodds, W. K., and Whiles, M. R., 2010. *Freshwater Ecology: Concepts and Environmental Applications of Limnology*, 2nd edn. Amsterdam: Academic.

FitzPatrick, E. A., 1993. *Soil Microscopy and Micromorphology*. Chichester: Wiley.

French, C. A. I., 2003. *Geoarchaeology in Action: Studies in Soil Micromorphology and Landscape Evolution*. London: Routledge.

Freytet, P., and Verrecchia, E. P., 2002. Lacustrine and palustrine carbonate petrography: an overview. *Journal of Paleolimnology*, **27**(2), 221–237.

Gastaldo, R. A., and Demko, T. M., 2011. The relationship between continental landscape evolution and the plant-fossil record: long term hydrologic controls on preservation. In Allison, P. A., and Bottjer, D. J. (eds.), *Taphonomy: Process and Bias Through Time*, 2nd edn. Dordrecht: Springer. Topics in Geobiology 32, pp. 249–285.

Gilbert, A. S., 1989. Microscopic bone structure in wild and domestic animals: a reappraisal. In Crabtree, P. J., Campana, D. V., and Ryan, K. (eds.), *Early Animal Domestication and Its Cultural Context*. Philadelphia: University Museum, University of Pennsylvania. MASCA Research Papers in Science and Archaeology, pp. 46–86.

Goldberg, P., and Macphail, R. I., 2006. *Practical and Theoretical Geoarchaeology*. Oxford: Blackwell.

Haas, J. N., and Magny, M., 2004. Schichtgenese und Vegetationsgeschichte. In Jacomet, S., Leuzinger, U., and Schibler, J. (eds.), *Die jungsteinzeitliche Seeufersiedlung Arbon- Bleiche 3: Umwelt und Wirtschaft*. Frauenfeld: Departement für Erziehung und Kultur des Kantons Thurgau. Archäologie im Thurgau 12, pp. 43–49.

Heitz-Weniger, A., 2014. Palynological investigations at the Late Bronze-Early Iron Age lakeshore settlement of Luokesa 1 (Moletai District, Lithuania): a contribution to the Middle-Late Holocene vegetation history of the south-eastern Baltic regions. *Vegetation History and Archaeobotany*, **23**(4), 383–402.

Holden, J., and Burt, T. P., 2003. Hydrological studies on blanket peat: the significance of the acrotelm-catotelm model. *Journal of Ecology*, **91**(1), 86–102.

Huisman, D. J., and Klaassen, R. K. W. M., 2009. Wood. In Huisman, D. J. (ed.), *Degradation of Archaeological Remains*. Den Haag: Sdu Uitgevers b.v., pp. 17–32.

Huisman, D. J., Lauwerier, R. C. G. M., Jans, M. M. E., Cuijpers, A. G. F. M., and Laarman, F. J., 2009. Bone. In Huisman, D. J. (ed.), *Degradation of Archaeological Remains*. Sdu Uitgevers b.v., pp. 33–54.

Ismail-Meyer, K., 2014. The potential of micromorphology for interpreting sedimentation processes in wetland sites: a case study of a late Bronze Age-early Iron Age lakeshore settlement at Lake Luokesa (Lithuania). *Vegetation History and Archaeobotany*, **23**(4), 367–382.

Ismail-Meyer, K., 2016. Organic matter. In Stoops, G., and Nicosia, C. (eds.), *Encyclopedia of Archaeological Soil and Sediment Micromorphology*. Wiley-Blackwell.

Ismail-Meyer, K., and Rentzel, P., 2004. Mikromorphologische Untersuchung der Schichtabfolge. In Jacomet, S., Leuzinger, U., and Schibler, J. (eds.), *Die jungsteinzeitliche Seeufersiedlung Arbon-Bleiche 3: Umwelt und Wirtschaft*. Frauenfeld: Departement für Erziehung und Kultur des Kantons Thurgau. Archäologie im Thurgau 12, pp. 66–80.

Ismail-Meyer, K., Rentzel, P., and Wiemann, P., 2013. Neolithic lakeshore settlements in Switzerland: new insights on site formation processes from micromorphology. *Geoarchaeology*, **28**(4), 317–339.

Jacomet, S., 1985. *Botanische Makroreste aus den Sedimenten des neolithischen Siedlungsplatzes AKAD-Seehofstrasse am untersten Zürichsee. Die Reste der Uferpflanzen und ihre Aussagemöglichkeiten zu Vegetationsgeschichte, Schichtentstehung und Seespiegelschwankungen*. Zürich: Juris Verlag. Zürcher Studien zur Archäologie. http://ipna.unibas.ch/archbot/pdf/1985_Jacomet%20_ZuerichAKAD.pdf.

Jacomet, S., and Brombacher, C., 2005. Reconstructing intra-site patterns in Neolithic lakeshore settlements: the state of archaeobotanical research and future prospects. In Della Casa, P., and Trachsel, M. (eds.), *WES'04 – Wetland Economies and Societies. Proceedings of the International Conference in Zurich, 10–13 March 2004*. Zürich: Chronos. Collectio Archæologica 3, pp. 69–94. http://ipna.unibas.ch/archbot/pdf/Jacomet_Brombacher_2005WES.pdf.

Jacomet, S., Leuzinger, U., and Schibler, J., 2004. Synthesis. In Jacomet, S., Leuzinger, U., and Schibler, J. (eds.), *Die jungsteinzeitliche Seeufersiedlung Arbon-Bleiche 3: Umwelt und Wirtschaft*. Frauenfeld: Departement für Erziehung und Kultur des Kantons Thurgau. Archäologie im Thurgau 12, pp. 380–416.

Jacomet, S., Latałowa, M., and Bittmann, F., 2014. The potential of palaeoecological studies in archaeological wetland sites of the southern Baltic regions. *Vegetation History and Archaeobotany*, **23**(4), 339–340.

Jans, M. M. E., Nielsen-Marsh, C. M., Smith, C. I., Collins, M. J., and Kars, H., 2004. Characterisation of microbial attack on archaeological bone. *Journal of Archaeological Science*, **31**(1), 87–95.

Karkanas, P., Pavlopoulos, K., Kouli, K., Ntinou, M., Tsartsidou, G., Facorellis, Y., and Tsourou, T., 2011. Palaeoenvironments and site formation processes at the Neolithic lakeside settlement of Dispilio, Kastoria, Northern Greece. *Geoarchaeology*, **26**(1), 83–117.

Keddy, P. A., 2010. *Wetland Ecology: Principles and Conservation*, 2nd edn. New York: Cambridge University Press.

Kenward, H., and Hall, A., 2000. Decay of delicate organic remains in shallow urban deposits: are we at a watershed? *Antiquity*, **74**(285), 519–525.

Kenward, H., and Hall, A., 2004. Actively decaying or just poorly preserved? Can we tell when plant and invertebrate remains in urban archaeological deposits decayed? In Nixon, T. J. P. (ed.), *Preserving Archaeological Remains In Situ? Proceedings of the 2nd (PARIS) Conference 12–14th September 2001*. London: Museum of London Archaeology Service, pp. 4–10.

Kenward, H., and Hall, A., 2008. Urban organic archaeology: an irreplaceable palaeoecological archive at risk. *World Archaeology*, **40**(4), 584–596.

Krier, V., 1997. Pemières observation micromorphologiques sur la coupe de Chalain 3. In Pétrequin, P. (ed.), *Chalain station 3 (3200–2900 av. J.-C.)*. Paris: Maison des sciences de l'homme, pp. 95–99.

Larsson, L., 2007. The ritual use of wetlands during the Neolithic: a local study in southernmost Sweden. In Lillie, M., and Ellis, S. (eds.), *Wetland Archaeology and Environments: Regional Issues, Global Perspectives*. Oxford: Oxbow Books, pp. 79–90.

Leuzinger, U., 2000. *Die jungsteinzeitliche Seeufersiedlung Arbon-Bleiche 3: Befunde*. Frauenfeld: Departement für Erziehung und Kultur des Kantons Thurgau. Archäologie im Thurgau 9.

Lewis, H., 2007. Pile dwellings, drainage and deposition: preliminary soil micromorphology study of cultural deposits from underwater sites at Lake Luokesas, Molėtai Region, Lithuania. *Journal of Wetland Archaeology*, **7**(1), 33–50.

Lillie, M., 2007. In situ preservation: geo-archaeological perspectives on an archaeological Nirvana. In Lillie, M., and Ellis, S. (eds.), *Wetland Archaeology and Environments: Regional Issues, Global Perspectives*. Oxford: Oxbow Books, pp. 156–172.

Lillie, M., and Ellis, S., 2007. Wetland archaeology and environments. In Lillie, M., and Ellis, S. (eds.), *Wetland Archaeology and Environments: Regional Issues, Global Perspectives*. Oxford: Oxbow Books, pp. 3–10.

Lillie, M., and Smith, R., 2009. *International Literature Review: In Situ Preservation of Organic Archaeological Remains for English Heritage (PNUM 5520)*. Hull: Wetland Archaeology and Environments Research Centre, Department of Geography, University of Hull. http://www2.hull.ac.uk/science/pdf/lit%20review.pdf.

Lindsay, R., 2010. *Peatbogs and Carbon: A Critical Synthesis*. London: University of East London, Environmental Research Group. www.rspb.org.uk/Images/Peatbogs_and_carbon_tcm9-255200.pdf.

Macphail, R. I., Allen, M. J., Crowther, J., Cruise, G. M., and Whittaker, J. E., 2010. Marine inundation: effects on archaeological features, materials, sediments and soils. *Quaternary International*, **214**(1–2), 44–55.

Magny, M., 2004. Holocene climate variability as reflected by mid-European lake-level fluctuations and its probable impact on prehistoric human settlements. *Quaternary International*, **113**(1), 65–79.

Magny, M., Leuzinger, U., Bortenschlager, S., and Haas, J. N., 2006. Tripartite climate reversal in Central Europe 5600–5300 years ago. *Quaternary Research*, **65**(1), 3–19.

Magny, M., Arnaud, F., Billaud, Y., and Marguet, A., 2012. Lake-level fluctuations at Lake Bourget (eastern France) around 4500–3500 cal. a BP and their palaeoclimatic and archaeological implications. *Journal of Quaternary Science*, **27**(5), 494–502.

Maier, U., 2011. Archäobotanische Flächenuntersuchungen in der endneolithischen Siedlung Torwiesen II. *Hemmenhofener Skripte*, **9**, 81–122.

Malterer, T. J., Verry, E. S., and Erjavec, J., 1992. Fiber content and degree of decomposition in peats: review of national methods. *Soil Science*, **56**(4), 1200–1211.

Marxsen, J., and Wagner, R., 2011. Particulate organic matter. In Wagner, R., Marxsen, J., Zwick, P., and Cox, E. J. (eds.), *Central European Stream Ecosystems: The Long Term Study of the Breitenbach*. Weinheim: Wiley-VCH, pp. 74–83.

Menotti, F., 2001. *The Missing Period: Middle Bronze Age Lake-Dwellings in the Alps*. Oxford: Archaeopress. British Archaeological Reports, International Series 968.

Menotti, F. (ed.), 2004. *Living on the Lake in Prehistoric Europe: 150 Years of Lake-Dwelling Research*. London: Routledge.

Menotti, F., 2012. *Wetland Archaeology and Beyond: Theory and Practice*. Oxford: Oxford University Press.

Meyers, P. A., and Ishiwatari, R., 1993. Lacustrine organic geochemistry – an overview of indicators of organic matter sources and diagenesis in lake sediments. *Organic Geochemistry*, **20**(7), 867–900.

Middleton, B., 1999. *Wetland Restoration. Flood Pulsing, and Disturbance Dynamics*. New York: Wiley.

Mitsch, W. J., and Gosselink, J. G., 2007. *Wetlands*, 4th edn. Hoboken: Wiley.

Monnier, J.-L., Pétrequin, P., Richard, A., Pétrequin, A.-M., and Gentizon, A.-L., 1991. *Construire une maison 3000 ans avant J. C.: Le lac de Chalain au Néolithique*. Paris: Errance.

Murphy, D. H., and Wilkinson, B. H., 1980. Carbonate deposition and facies distribution in a central Michigan marl lake. *Sedimentology*, **27**(2), 123–135.

Nicholas, G. P., 2012. Towards an anthropology of wetland archaeology: hunter-gatherers and wetlands in theory and practice. In Menotti, F., and O'Sullivan, A. (eds.), *The Oxford Handbook of Wetland Archaeology*. Oxford: Oxford University Press, pp. 761–778.

Pawluk, S., 1987. Faunal micromorphological features in moder humus of some Western Canadian soils. *Geoderma*, **40**(1–2), 3–16.
Platt, N. H., and Wright, V. P., 1991. Lacustrine carbonates: facies models, facies distribution and hydrocarbon aspects. In Anadón, P., Cabrera, L., and Kelts, K. (eds.), *Lacustrine Facies Analysis*. Oxford: Blackwell. International Association of Sedimentologists, Special Publication 13, pp. 57–74.
Pollmann, B., 2014. Environment and agriculture of the transitional period from the Late Bronze to early Iron Age in the eastern Baltic: an archaeobotanical case study of the lakeshore settlement Luokesa 1, Lithuania. *Vegetation History and Archaeobotany*, **23**(4), 403–418.
Ramsar Convention Secretariat, Gland, Switzerland: www. ramsar. org..
Rentzel, Ph., Nicosia, C., Gebhard, A., Pümpin, Ch., Ismail-Meyer, K., and Brönnimann, D., 2016. Trampling features. In Nicosia, C., and Stoops, G. (eds.), *Encyclopedia of Archaeological Soil and Sediment Micromorphology*. Chichester: Wiley-Blackwell.
Retallack, G., 1984. Completeness of the rock and fossil record: some estimates using fossil soils. *Paleobiology*, **10**(1), 59–78.
Ruoff, U., 2004. Lake-dwelling studies in Switzerland since 'Meilen 1854'. In Menotti, F. (ed.), *Living on the Lake in Prehistoric Europe: 150 Years of Lake-Dwelling Research*. New York: Routledge, pp. 9–21.
Schoch, W. H., Heller, I., Schweingruber, F. H., and Kienast, F., 2004. Wood Anatomy of Central European Species: http://www.woodanatomy.ch.
Schweingruber, F. H., 1982. *Mikroskopische Holzanatomie/Microscopic Wood Anatomy*, 2nd edn. Teufen: F. Flück-Wirth.
Stolt, M. H., and Lindbo, D. L., 2010. Soil organic matter. In Stoops, G., Marcelino, V., and Mees, F. (eds.), *Interpretation of Micromorphological Features of Soils and Regoliths*. Amsterdam: Elsevier, pp. 369–396.
Stoops, G., 2003. *Guidelines for Analysis and Description of Soil and Regolith Thin Sections*. Madison: Soil Science Society of America.
Turnbaugh, W. A., 1978. Floods and archaeology. *American Antiquity*, **43**(4), 593–607.
Turner-Walker, G., and Mays, S., 2008. Histological studies on ancient bone. In Pinhasi, R., and Mays, S. (eds.), *Advances in Human Palaeopathology*. Chichester: Wiley, pp. 121–146.
Van der Valk, A., 2006. *The Biology of Freshwater Wetlands*. Oxford: Oxford University Press.
Vernimmen, T. J. J., 2002. The preservation of botanical remains in archaeological sites on Voorne-Putten. In van Heeringen, R. M., and Theunissen, E. M. (eds.), *Desiccation of the Archaeological Landscape at Voorne-Putten, the Netherlands*. Amersfoort: Rijksdienst voor het Oudheidkundig Bodemonderzoek. Nederlandse Archaeologische Rapporten 25, pp. 137–162.
Wallace, G. E., 2000. *A Microscopic View of Neolithic Lakeside Settlements on the Northern Rim of the European Alps*. Unpublished Ph.D. thesis, University of Cambridge.
Wallace, G., 2003. Using narrative to contextualise micromorphological data from Neolithic wetland houses. *Journal of Wetland Archaeology*, **3**(1), 75–92.
Wetzel, R. 2001. *Limnology: Lake and River Ecosystems*. San Diego:Academic Press, 1006 p.
Wiemann, Ph., and Rentzel, Ph. 2015. Micromorphological studies on wetland site formation processes: additional help for a better understanding of the lake-dwellings' final disappearance. In Menotti, F. (ed.), *The end of the lake-dwellings in the Circum-Alpine region*. Oxford. p.101-124.
Zolitschka, B., Behre, K.-E., and Schneider, J., 2010. Human and climatic impact on the environment as derived from colluvial, fluvial and lacustrine archives – examples from the Bronze Age to the Migration period, Germany. *Quaternary Science Reviews*, **22**(1), 81–100.

Cross-references

Inundated Freshwater Settings
Organic Residues
Paleoenvironmental Reconstruction
Paleoshores (Lakes and Sea)
Sedimentology
Site Formation Processes
Site Preservation
Soil Micromorphology
Trampling

PASTORAL SITES

Giovanni Boschian
Dipartimento di Biologia, Università di Pisa, Pisa, Italy

Definition

Pastoral sites are those devoted to or based on livestock raising. This definition should be applied with care, because stock rearing may have played a variable role in the economies of past populations, and consequently, traces of pastoral activities may be more or less evident in sites where other subsistence practices were more apparent. In the majority of cases, the term applies to cultural contexts in which a production economy was at least partly engaged in pastoral pursuits for subsistence. Through time, pastoral sites were integrated into economic systems of increasing complexity, and they also included settlements with different pastoral functions, many of which exploited, managed, and modified the surrounding and intervening territories.

Introduction

Due to the diffusion of stock rearing practices from its earliest appearances, pastoral sites are widespread and can be found in extremely diverse environments from the lowest latitudes to the edge of the polar ice caps and from lowlands to high mountains. As a result, a very wide range of "natural" geological processes can be involved in the formation processes of these sites. These processes will be not treated here, as more information about them can be found in specific manuals.

On the other hand, the anthropogenic and human-influenced animal components tend to be less variable and depend more on the animal species involved than on specific practices connected with pastoral economy or – more simply – with stock rearing. Nevertheless, it must be noted that the species of animals raised are partly a consequence of the environmental characteristics of the area where the sites are located. This entry will focus on the components that are distinctive of pastoral sites.

Eventually, it can be argued that pastoral sites may represent just a minimal part of much larger agropastoral systems of landscape use, because animals (and shepherds) spend more time on pastures than in the limited areas that are normally considered to be typical pastoral sites in the strict context of a settlement site. Unfortunately, the traces directly left by ancient shepherds and their flocks on the landscape are ephemeral and elusive, and their preservation through time is unlikely. Conversely, indirect results of pastoral activities may leave strong traces on the landscape (soil erosion, scree activation, etc.), which also fall under the category of more general geological studies and of landscape archaeology.

Pastoral site typology

Livestock raising is generally presumed to be a high-mobility activity, with animals moving over more or less wide territories on daily and/or seasonal cycles. Therefore, populations or groups relying on pastoral economies or more simply shepherds, live nomadic or seminomadic lifestyles, and their settlements tend to be characterized by ephemeral or movable/transportable dwellings, like huts or tents (Simms, 1988), whose traces in the archaeological record can be extremely scanty, if they are preserved at all. During the night or in other peculiar occasions connected with the management of the flocks, animals can be kept in pens delimited by wattle or fences, or by less precarious stone walls. In such cases, postholes or stone alignments/accumulations may be the only trace of the presence of domestic animals on the territory, even if it is argued that it may be quite difficult to find clear traces of organization in the generally random clusters of postholes that derive from the periodic shifting and rebuilding of pens. Caves and rock-shelters are typical places on the landscape where flocks can be stabled to provide shelter from rain and safety from predators. Such sites were exploited for stabling animals from the Neolithic onwards throughout Mediterranean Europe (Angelucci et al., 2009, and literature therein), and in several areas, they are still being used today for the same purpose.

Domestic animals can share spaces more or less closely with humans in more stable settlements, like villages and proto-urban or urban sites (Matthews, 2010). In these cases, the problems are approximately the same, because the animals – if not sharing dwelling spaces with humans – may be kept in specific enclosures or buildings whose traces in the stratigraphic sequences may also be unclear. Even if traces of animal husbandry are quite evident and abundant, as indicated by meter-thick coprogenic deposits that commonly fill spaces between houses in Near Eastern tells, these sites cannot be considered as strictly pastoral but more like mixed economy (agropastoral) settlements.

Indicators of pastoral activities

Pastoral signals introduced into a site by continuing relationships between humans and livestock include two basic indicators that suggest the permanence of animals: bones and droppings. The archaeological significance of coprogenic material is much more diagnostic than that of zooarchaeological data because animals may have been kept for reasons other than meat consumption and consequently may not have been butchered on-site. Therefore, “Dung is sounder evidence of the presence of flocks than sheep bones are” (Boschian and Montagnari-Kokelj, 2000, 347). Most aspects of dung in anthropogenic contexts, like its composition, accumulation modes, preservation versus decay, and archaeological significance, were thoroughly examined by Shahack-Gross (2011).

Macro- and microscopic scale indicators of dung in sediments were first identified by J. É. Brochier (1983) in a seminal study of fine-grained sediments in Neolithic cave contexts in France. Later, these indicators were better formalized (Courty et al., 1989; Brochier, 2002; Shahack-Gross, 2011). Such evidence should nevertheless be evaluated with care and its significance confirmed using other cultural markers, because the clues may point to spontaneous stabling of wild animals, as in the case of the chamois or ibex dung occurring in the Balma Margineda rock-shelter between the Younger Dryas and Early Atlantic (Brochier, 1991).

The most reliable indicators of the presence of dung within archaeological deposits can be observed at the microscopic scale using micromorphological techniques: spherulites, phytoliths, and ash, the former being sufficient indicators, while the others make sense when all the indicators are found in association. Ash occurs when dung is burned, which happened often in most cases. Charcoal is almost always associated with these components as well, even if it may derive also from a very wide range of other activities.

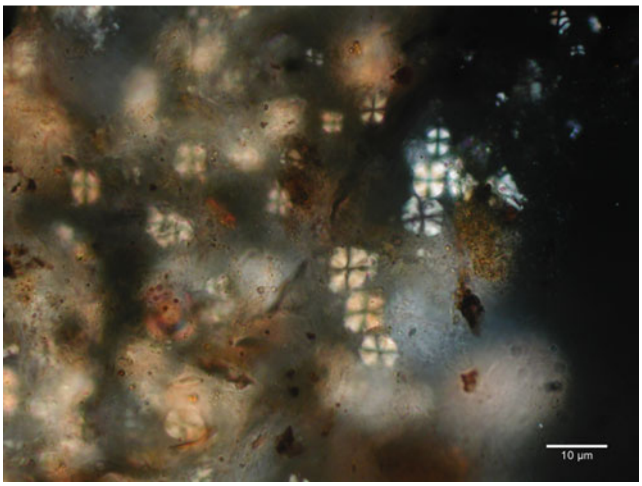
Spherulites (Canti, 1997, 1998) are extremely common in herbivore dung because they are produced within the ruminant gut during the digestion process – but see also Courty et al. (1989) for occurrence in the dung of nonruminants. They are made up of acicular calcareous crystals radially arranged in spheres whose diameter can range from 4–5 to 10–12 or sometimes up to 20 μm (Figure 1); they are transparent and colorless and can be easily detected under crossed polars because of their cross-shaped pseudo-interference figure. When burned, they may have a dark blackish, almost opaque core.

It should be pointed out that even if spherulites are almost certain indicators of ruminant dung, their absence is not conclusive of the absence of dung. In fact, not all ruminants produce spherulites, or they may produce them in variable amounts depending on season, fodder type, etc. Moreover, spherulites may decay and disappear from the sediments. These aspects were recently stressed by Lancelotti and Madella (2012), whose actualistic work on dung fuel cakes suggests that an association of phytolith and chemical analyses may help in sorting out the occurrence of dung.

Hydrated silica phytoliths commonly occur in dung, as indigestible by-products of grass-fed animal alimentation, but they may be present in archaeological deposits because of other practices connected to pastoral or even pre-pastoral use, like accumulation of fodder or litter for animals (Courty et al., 1991; Macphail et al., 1997;

Boschian and Montagnari-Kokelj, 2000; Brochier and Claustre, 2000; Boschian, 2006), as well as from a wide range of non-pastoral activities. This aspect, and mostly the accumulation of special types of fodder, is particularly relevant in Early Holocene horizons of some Saharan pastoral caves, as inferred from the results of multidisciplinary studies (Cremaschi et al., 1996; Cremaschi and Trombino, 1999; Di Lernia, 2001).

Ash is also a frequently occurring component of sediments generated by pastoral activities, though obviously not exclusively. Ash comprises micrite aggregates that are pseudomorphic after calcium oxalate cubes, lozenges, crescents, and other regular crystalline shapes (Figure 2); they result from the burning and re-liming of 1- or 2-hydrated calcium oxalate (whewellite and weddellite, respectively) crystals that occur in wood, leaves, bark, and other vegetal tissues (Canti, 2003). At higher temperatures, these aggregates may collapse and produce a very fine micritic "dust" with petrographic interference colors that are relatively low compared with the typical calcite ones.

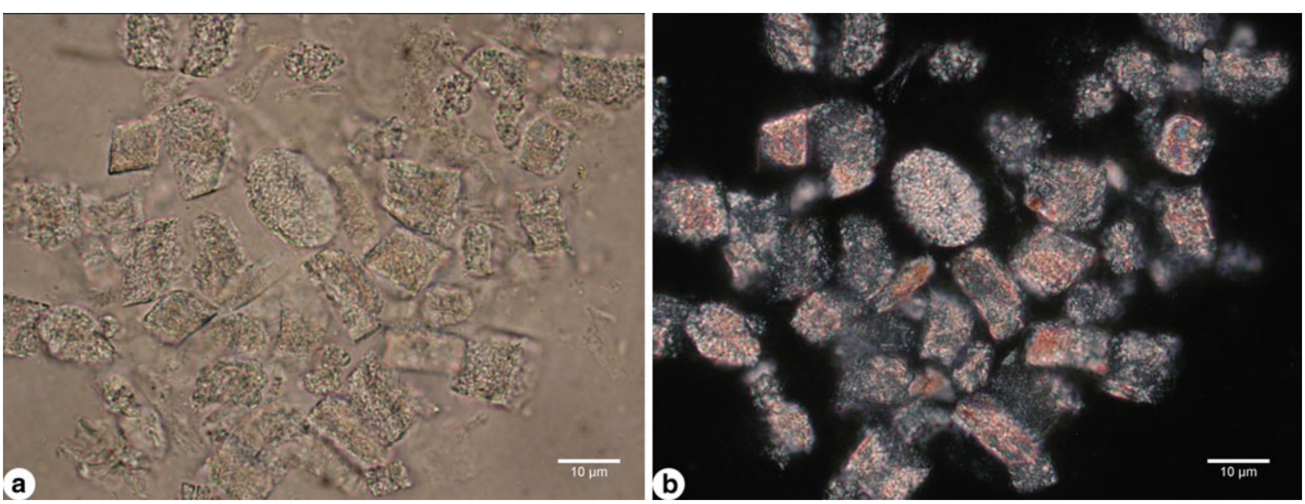


Pastoral Sites, Figure 1 Photomicrograph of fecal spherulites. Note the black crosses (pseudo-interference figures), which are characteristic of these features under crossed polarizers. S. Angelo Cave (Abruzzo, Central Italy), Middle Neolithic Painted Ware levels. 100× oil immersion objective, crossed polarizers.

Rock polish may result from the stabling of livestock in caves and rock-shelters, and it may be used as a reasonably reliable indicator of pastoral practices. This polish is due to the rubbing of sheep and goat fleece on the walls of the caves where large flocks are crowded, and it appears as a smoothed and glossy band of rock, some tens of centimeters wide. Its height above the cave floor corresponds roughly to the size of the sheep, but its present-day position on the wall can be much higher than the floor, indicating changes in cave sediment thickness. These changes may be due to erosional processes emptying the cave, as well as volume reduction due to intentional burning of the dung accumulation. The latter can be a common practice in pastoral caves, where the whole inner volume can be quickly filled up by dung after occupations by large flocks (Brochier et al., 1992).

Coprogenic sedimentary facies

The abovementioned basic components are usually organized into two main deposit facies that can be easily identified at the macroscopic scale. Nonetheless, these facies are usually variable, and several subtypes with intermediate characteristics can also be observed.



Pastoral Sites, Figure 2 Photomicrograph of *Tilia cordata* (European lime or linden tree) experimental ash. Micrite pseudomorphs on Ca-oxalate crystals. 100× oil immersion objective, (**a**) plane polarized light, (**b**) crossed polarizers.

Pastoral Sites, Figure 3 Homogeneous coprogenic facies. Brownish homogeneous or poorly layered horizons mostly comprising randomly dispersed spherulites, phytoliths, and ash, interlayered with black/white lenses of ashed coprolites. Zemunica Cave (Dalmacija, Southern Croatia), Neolithic to Bronze Age levels. Distance between white markers, 50 cm.

Homogeneous facies

Seen with the unaided eye, this facies appears to contain brownish to grayish homogeneous deposits, often somewhat thick and sometimes crossed by isolated thin black/white lenses that may be several square meters wide (Figure 3). Unsorted stones can also occur, usually scattered randomly throughout the sediment. The soil strength class is "moderately weak to moderately firm," i.e., dry sediment blocklets fail if gently to firmly pressed between the forefinger and thumb (Catt, 1991).

At the microscopic scale, the bulk of this facies comprises phytoliths and spherulites, randomly scattered throughout the sediment and creating a homogeneous and compact mass with few voids. In some cases, the spherulites are even more abundant and apparently prevail over the phytoliths. Micrite aggregates pseudomorphic on oxalate crystals (ash) are present in various quantities in these sediments, and their aspect is grayish and "dusty" under plane polarized light. Small bits of amorphous organic matter are ubiquitous, the larger ones sometimes preserving traces of vegetal tissues. Charcoal may also occur, in variable quantities. Sand- to fine silt-size silicate grains may occur within this facies, depending on the geological characteristics of the surrounding environment.

"Layer-cake" facies

At the macroscopic scale, this facies is typically banded black and white, with strikingly regular alternating horizons that, in fact, represent pairs of layers or lenses that can be very dark gray to black and grayish to brownish to very light gray. After drying, these colors become black and light gray to whitish (Figure 4). The individual horizons are thin (2–3 cm for the dark ones, up to 10–12 cm for the light ones) by comparison to their extension, which may be up to several square meters. The matrix possesses grain sizes in the range of sandy silt loam to sandy loam; the coarse component of the sediment is rare and comprises randomly scattered angular stones of various sizes. The soil strength class is "moderately weak to moderately firm," i.e., dry sediment blocklets fail if gently to firmly pressed between the forefinger and thumb (Catt, 1991). These deposits – called *fumiers* by French authors – are typical of caves used for stabling animals and can be considered diagnostic even at a macroscopic scale. These sequences are often interrupted, or vertically crossed, by thin vertical features, probably postholes that testify to the use of wattle or wooden enclosures.

The dark horizon always represents the bottom horizon of the pair; it is usually thinner than the overlying lighter part, and in some cases, it can also be discontinuous. The structure is medium to well-developed very fine to fine granular, with large pores and rather loose. The light horizon is less porous and more compact, and sometimes it includes two or three subfacies that differ in texture, color, and porosity and that are organized in mottles and patches or in layers bounded by complex surfaces. The limits between these units are generally sharp and plain or very slightly undulating.

This facies can occur in isolated pairs usually embedded within the homogeneous facies (see above) or in homogeneously layered decks. These decks can be up to several meters thick and somewhat domed, resembling a sort of finely layered "heap."

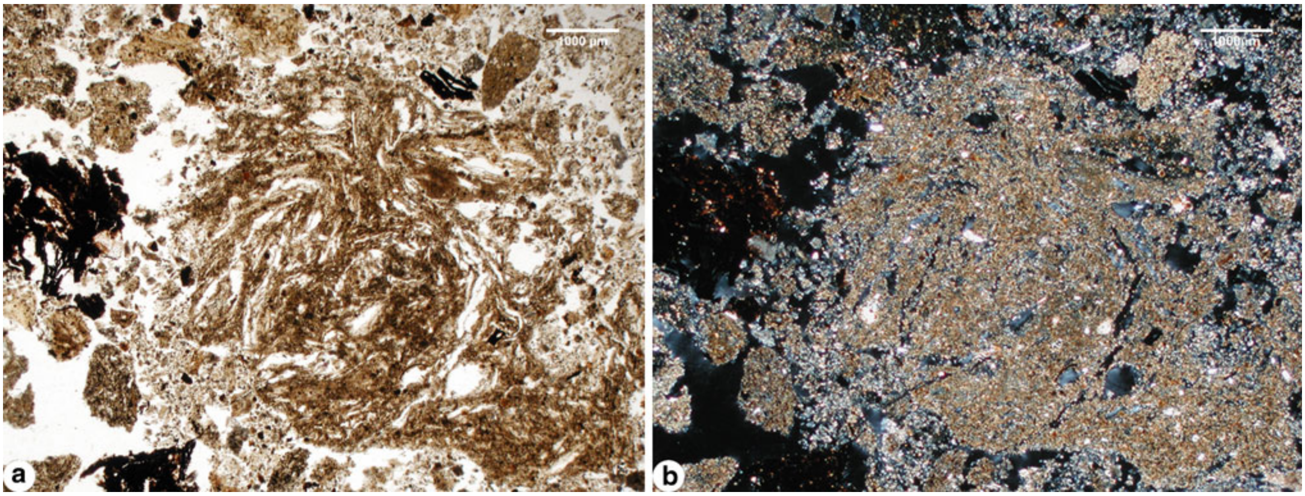
Pastoral Sites, Figure 4 Layer-cake coprogenic facies. Alternating grayish/whitish and black levels comprising completely ashed coprolites (often with layered-undulating microstructure) and dark charred coprolites with vegetal residues, respectively. The white lenses are made up almost exclusively of phytoliths. Vela Cave (Istria Peninsula, Northern Croatia). Frame height about 42 cm.

At the microscopic scale, the dark levels are mainly made up of partially to almost completely charred vegetal remains, mostly leaves, twigs, and young wood fragments. These can be quite large, up to 10–15 mm or more, and preserve their original structure. Under crossed polarizers, they are usually amorphous, though some weak birefringence can be detected in the less charred fragments. Micrite aggregates pseudomorphic on Ca-oxalate crystals and higher temperature ash are relatively frequent, as well as calcareous spherulites. The organization of the white layers at the microscopic scale is somewhat more complicated and may include different subfacies, which apparently do not follow a specific cyclical sequence. The most relevant ones are the granular and the finely layered subfacies.

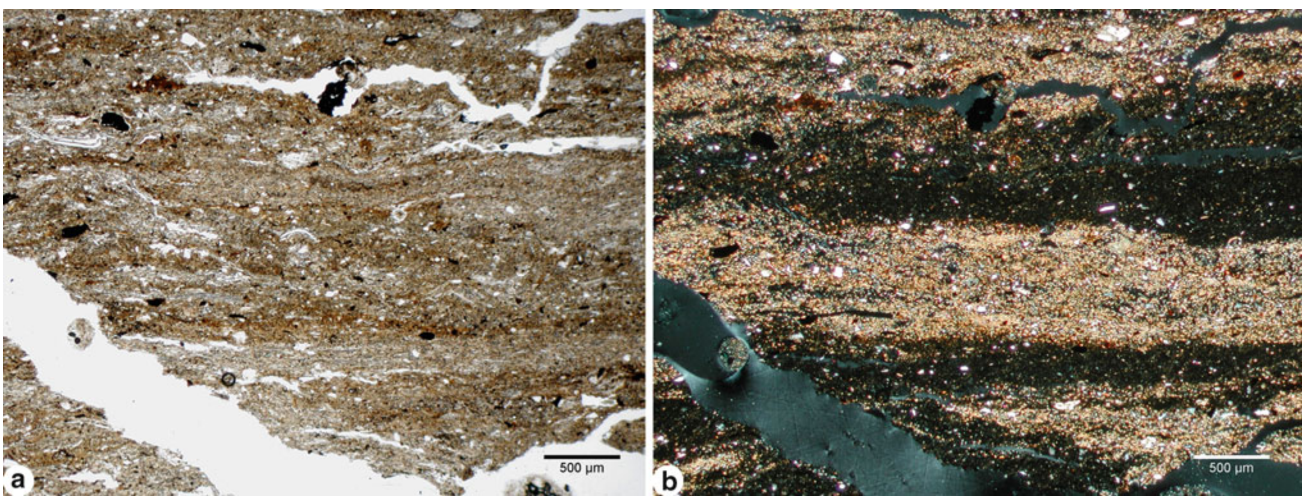
The granular subfacies is composed mainly of subrounded to slightly elongated aggregates of organic remains (Figure 5); these aggregates are poorly sorted, ranging from few hundreds of micrometers to about 1–2 cm. They are made up of fibrous features 5–20 μm thick and up to 1–2 mm long, which are made up of partially articulated hydrated silica phytoliths and transparent colorless to semiopaque brownish organic matter that, in some cases, may have been partly transformed to carbonates by ashing. The size and spatial organization of the fibrous features often depend on the shape of the aggregates; they are somewhat short and randomly compressed within the subspherical aggregates or sometimes longer and arranged in less compact wavy bundles inside the elongated aggregates. Spherulites are often present within the aggregates. The packing voids between aggregates are (partly) filled by a matrix of spherulites, phytoliths, amorphous organic matter, and mineral components embedded in a fine micritic micromass. Therefore, this micromass may be brightly colored by high-order interference colors under crossed polarizers.

These rounded aggregates are interpreted as sheep/goat droppings, which are typically pellet shaped, whereas the elongated ones with fluidal fabric represent cattle droppings.

The finely layered subfacies is characterized by a fine lamination of regularly alternating lighter and darker layers that are slightly undulating, with sharp or clear limits, 60–80 to 2,000–3,000 μm thick, and with a homogeneous micromass (Figure 6). The light ones are almost transparent and colorless under plane polarized light and show an amorphous b-fabric under crossed polarizers; they are made up almost entirely of hydrated silica phytoliths with a few fine silicate grains. The phytoliths are often articulated and regularly arranged parallel to the layer limits, building up some sort of "fluidal" feature. By eye, they usually appear whitish. The darker layers have a brown-yellowish color under plane polarized light and a crystallitic b-fabric under crossed polarizers; they are made up of phytoliths, bits of amorphous organic matter, fine silicate grains, spherulites, and micrite. The pores may range from frequent to totally absent, and they may be elongated with their longer axes parallel to the layering, while the phytoliths are usually not regularly arranged as they are within the light layers. Micrite aggregates



Pastoral Sites, Figure 5 Photomicrograph of granular subfacies. Medium to poorly developed granular microstructure, the aggregates are burned sheep/goat coprolites, including remains of convolute vegetal fibers. Spherulites and some mineral (quartz) grains can be observed under crossed polarizers. S. Angelo Cave (Abruzzo, Central Italy). 2.5× objective, (**a**) plane polarized light, (**b**) crossed polarizers.



Pastoral Sites, Figure 6 Photomicrograph of microlaminated undulating facies. Thin beds of phytoliths (dark under crossed polarizers), sometimes mixed with sparse mineral grains, alternating with levels rich in spherulites, with variable amounts of ash, phytoliths, and mineral grains (bright under plane polarized light). In the upper left corner, a reddish aggregate of *terra rossa*-like soil (Alfisol) was probably transported into the cave under the sheep/goat feet. Pupićina Cave (Istria Peninsula, Northern Croatia). 2.5× objective, (**a**) plane polarized light, (**b**) crossed polarizers.

pseudomorphic on Ca-oxalates (ash) may occur in variable amounts in the darker layers. Ash may be dominant in some of these levels.

Significance of coprogenic sediments

The interpretation of these sediments is reasonably straightforward and relies mostly on micromorphological and microstratigraphic observations, as well as on geo-ethnoarchaeological considerations. The information obtained at the lowest interpretive level explains mostly the formation processes of single lithological units and homogeneous sequences of units, whereas complex inference about site use, distribution of activity spaces, and diachronic evolution of the site derive from higher level interpretation, which involves the study of cultural remains and faunas and the assessment of the chronological framework.

Regarding the layer-cake sequences, the black levels embed charred plant remains, mostly young wood and leaves, and partially burned coprolites. Conversely, the white levels are made up of thoroughly ashed, more or less fragmented, and usually well-compacted coprolites and possibly some completely burned wood remains. In fact, each black/white pair resulted from the burning of one layer deposited during one phase of livestock stabling. Twigs and grass were initially laid down, as their remains are observed at the bottom where they are most frequent; they probably represent litter and/or fodder that can hardly be differentiated by soil micromorphology or other techniques (Brochier and Claustre, 2000, 469). Subsequently, they were covered by the droppings of the animals living upon them.

The evidence indicates that the dung (and possibly straw, hay, or even young branch litter remains) was systematically burned after the end of the stabling period, an operation performed in order to reduce the volume of the deposit and possibly in an attempt to sanitize the pen interiors. Stabling, burning, and abandonment were cyclically repeated, probably following a transhumant routine. The dung layer burned slowly because it was compacted by animal trampling and partially soaked by their liquid micturitions or by karstic drip water. The bottom part of each pair burned in a low oxygen environment, and thus its organic components were (partially) charred leading to the formation of a dark horizon. Conversely, the upper part burned under high-oxygen conditions and its vegetal components were thoroughly ashed, thereby creating the white layer. The very well-defined laminations indicate trampling, with consequent compaction of the dung or dung-rich sediment, and the rearrangement of elongated particles perpendicular to the compressive forces.

Unfortunately, the meaning of the homogeneous facies is still not fully clear. The basic components are the same as in the layer-cake facies, even if the degree of organization is almost null, and its components show a completely random distribution. It may be inferred that both facies originated from the stabling of domesticated herbivores. J. É. Brochier (2002) suggests that they may derive from complete primary mineralization of the organic components of herbivore dung without burning, and he employs the Provençal term *migon*. This process would result in a much lower final volume of deposit, and it would yield a complete rearrangement and randomization of the original fabric.

At a higher interpretive level, one should first observe that these basic sediment facies do not always fill up caves with continuous homogeneous sequences, but they are frequently juxtaposed laterally to other coprogenic facies or to sediments originating from domestic habitation. This may indicate specific spatial partitions within the cave, which sometimes change through time as some areas previously occupied by humans were later occupied by animals. This aspect is also reflected in the distribution of artifacts, which is usually lowest in the layer-cake facies and higher elsewhere. Two ideal extremes can be envisaged: (1) caves (or facies) mostly containing spherulites and phytoliths, and characterized by a low concentration of cultural remains, were used almost uniquely for penning animals, and (2) caves (or facies or lateral associations of facies) containing mostly ash and substantial amounts of cultural remains served mostly as shelters for humans. The variability is extreme between these two alternatives and provides a basis for complex interpretations about site use, links with lowland open-air sites, and complex land exploitation systems (Brochier et al., 1999; Brochier, 2002; Boschian and Miracle, 2007).

Caves versus open-air pastoral sites

Though they are not exclusively found there, the abovementioned deposits can be best observed in caves and rock-shelters, where they are well preserved because of the relatively limited action of water percolation. In fact, the specific surface areas of the particulate matter within these very fine-grained deposits are extremely large. As a result, the reactivity of the carbonate component (spherulites and micrite aggregates pseudomorphic on Ca-oxalates) is extremely high when affected by CO_2-acidified water. A major part of the diagnostic evidence that demonstrates prior pastoral uses (spherulites) may be rapidly destroyed in open-air contexts within relatively moist regions, unless the carbonate-rich horizons are shielded by reasonably impermeable overlying layers.

As observed by Shahack-Gross et al. (2003) regarding East African open-air contexts, enclosures for livestock are typical of pastoral sites, and they can be considered to be indicators of penning. This assumption is generalizable to other areas and cultures, and it is valid for open-air sites and caves, but it becomes stronger evidence in the former because of the more thorough deterioration of the coprogenic sediments due to alteration from the action of rainwater flowing through the site earth. Following the results of a geoarchaeological and ethnoarchaeological approach, the occurrence of a "microlaminated undulating structure . . . composed of alternating laminae of acellular organic matter and opal phytoliths" (Shahack-Gross et al., 2003, 450), in association with large amounts of grass phytoliths, calcareous spherulites, and authigenic phosphates, was identified as strongly suggestive of degraded enclosure sediments. Nonetheless, it was also argued that complications may frequently arise in identifying the concurrence of these markers (Shahack-Gross et al., 2008, and literature therein), whereas stable nitrogen isotope measures on bulk sediment samples are apparently more reliable, showing a major concentration of ^{15}N in enclosure deposits, and may be used to provide supplementary evidence in uncertain contexts. Conversely, carbon isotope ratios are not affected by site use, but they may give hints about the composition of the herds, indicating C3 (browsers) versus C4 (grazers) ratios.

Summary

Pastoral sites are usually more or less ephemeral campsites or settlements, in which the main activities are connected to livestock raising. Pastoral caves were used for stabling animals temporarily, in connection with more complex agropastoral systems of land exploitation that implied transhumance. Typical features of pastoral (cave or open-air) sites are enclosures used to pen the animals.

Calcareous spherulites, grass phytoliths, and authigenic phosphates, usually organized into microlaminated undulating microstructures, all resulting from animal dung accumulation, are the best indicators of pastoral sites. Nitrogen isotope analyses can be used as accessory indicators in open-air sites, where calcareous components may undergo dissolution and leaching and where the microstructures may be reworked.

Various coprogenic sediment facies can be observed within pastoral caves, where the preservation of the sediments is optimal; these can be used as indicators of specific pastoral practices, including transhumance and cyclical burning of the dung accumulations.

Bibliography

Angelucci, D. E., Boschian, G., Fontanals, M., Pedrotti, A., and Vergès, J. M., 2009. Shepherds and karst: the use of caves and rock-shelters in the Mediterranean region during the Neolithic. *World Archaeology*, **41**(2), 191–214.

Boschian, G., 2006. Geoarchaeology of Pupićina cave. In Miracle, P. T., and Forenbaher, S. (eds.), *Prehistoric Herders of Northern Istria: The Archaeology of Pupićina Cave*. Pula: Archaeological Museum of Istria. Monografije i katalozi 14, Vol. 1, pp. 123–162.

Boschian, G., and Miracle, P. T., 2007. Shepherds and caves in the karst of Istria (Croatia). In Boschian, G., (ed.), Proceedings of the Second International Conference on Soils and Archaeology, Pisa, Italy, May 12–15, 2003. *Atti Società Toscana Scienze Naturali, Memorie, Serie A*, Vol. **112**, pp. 173–180.

Boschian, G., and Montagnari-Kokelj, E., 2000. Prehistoric shepherds and caves in the Trieste Karst (Northeastern Italy). *Geoarchaeology*, **15**(4), 331–371.

Brochier, J., 1983. Bergeries et feux de bois néolithiques dans le Midi de la France: caractérisation et incidence sur le raisonnement sédimentologique. *Quartär*, **33–34**, 181–193.

Brochier, J., 1991. Géoarchéologie du monde agropastoral. In Guilaine, J. (ed.), *Pour une archéologie agraire: à la croisée des sciences de l'homme et de la nature*. Paris: A. Colin, pp. 303–322.

Brochier, J., 2002. Les sédiments anthropiques: méthodes d'étude et perspectives. In Miskovski, J.-C. (ed.), *Géologie de la Préhistoire: méthodes, techniques, applications*. Paris: Association pour l'étude de l'environnement géologique de la préhistoire, pp. 453–477.

Brochier, J. É., and Claustre, F., 2000. Le parcage des bovins et le problème des litières du Néolithique final à l'Âge du Bronze dans la Grotte de Bélesta. In Gascó, J., and Treinen-Claustre, F. (eds.), *Habitats, économies et sociétés du Nord-Ouest mé diterranéen de l'Age du bronze au premier Age du fer: XXIVe Congrès préhistorique de France, Carcassonne, 26–30 septembre 1994: actes du colloque international*. Paris: Societé Préhistorique Française, Vol. 3, pp. 27–36.

Brochier, J. É., Villa, P., Giacomarra, M., and Tagliacozzo, A., 1992. Shepherds and sediments: geo-ethnoarchaeology of pastoral sites. *Journal of Anthropological Archaeology*, **11**(1), 47–102.

Brochier, J.-L., Beeching, A., Sidi Maamar, H., and Vital, J., 1999. Les grottes bergeries des Préalpes et le pastoralisme alpin, durant la fin de la préhistoire. In Beeching, A. (ed.), *Circulations et identités culturelles alpines à la fin de la préhistoire. Materiaux pour un étude*. Valence: Centre d'Archéologie préhistorique de Valence. Travaux du Centre d'Archéologie préhistorique de Valence, Vol. 2, pp. 77–114.

Canti, M. G., 1997. An investigation of microscopic calcareous spherulites from herbivore dungs. *Journal of Archaeological Science*, **24**(3), 219–231.

Canti, M. G., 1998. The micromorphological identification of faecal spherulites from archaeological and modern materials. *Journal of Archaeological Science*, **25**(5), 435–444.

Canti, M. G., 2003. Aspects of the chemical and microscopic characteristics of plant ashes found in archaeological soils. *Catena*, **54**(3), 339–361.

Catt, J. A. (ed.), 1991. Paleopedology manual. *Quaternary International* **6**, 1–95.

Courty, M. A., Goldberg, P., and Macphail, R. I., 1989. *Soils and Micromorphology in Archaeology*. Cambridge: Cambridge University Press.

Courty, M. A., Macphail, R. I., and Wattez, J., 1991. Soil micromorphological indicators of pastoralism; with special reference to Arene Candide, Finale Ligure, Italy. In Maggi, R., Nisbet, R., and Barker, G. (eds.), *Atti della tavola rotonda internazionale: Archeologia della pastorizia nell'Europa meridionale, Chiavari, 22–24 settembre 1989, Museo archeologico per la preistoria e protostoria del Tigullio*. Bordighera: Istituto internazionale di studi liguri, Museo Bicknell. Rivista di Studi Liguri 57, Vol. 2, pp. 127–150.

Cremaschi, M., and Trombino, L., 1999. A micromorphological approach to the site formation processes. In di Lernia, S. (ed.), *The Uan Afuda Cave: Hunter-gatherer Societies of Central Sahara*. Florence: All'Insegna del Giglio. Arid Zone Archaeology Monographs, Vol. 1, pp. 27–38.

Cremaschi, M., di Lernia, S., and Trombino, L., 1996. From taming to pastoralism in a drying environment. Site formation processes in the shelters of the Tadrart Acacus massif (Libya, central Sahara). In Castelletti, L., and Cremaschi, M. (eds.), *Micromorphology of Deposits of Anthropogenic Origin*. Forlì: ABAC-O. XIIIth International Congress of Prehistoric and Protohistoric Sciences, vol. 3 Colloquium VI, pp. 87–106.

Di Lernia, S., 2001. Dismantling dung: delayed use of food resources among Early Holocene foragers of the Libyan Sahara. *Journal of Anthropological Archaeology*, **20**(4), 408–441.

Lancelotti, C., and Madella, M., 2012. The 'invisible' product: developing markers for identifying dung in archaeological contexts. *Journal of Archaeological Science*, **39**(4), 953–963.

Macphail, R. I., Courty, M.-A., Hather, J., Wattez, J., Ryder, M., Cameron, N., and Branch, N. P., 1997. The soil micromorphological evidence of domestic occupation and stabling activities. In Maggi, R., Starnini, E., and Voytek, B. (eds.), *Arene Candide: A Functional and Environmental Assessment of the Holocene Sequence (Excavations Bernabò Brea-Cardini 1940–50)*. Roma: Il Calamo. Memorie dell'Istituto Italiano Paleontologia Umana, Nuova serie 5, pp. 53–88.

Matthews, W., 2010. Geoarchaeology and taphonomy of plant remains and microarchaeological residues in early urban environments in the Ancient Near East. *Quaternary International*, **214**(1–2), 98–113.

Shahack-Gross, R., 2011. Herbivorous livestock dung: formation, taphonomy, methods for identification, and archaeological significance. *Journal of Archaeological Science*, **38**(2), 205–218.

Shahack-Gross, R., Marshall, F., and Weiner, S., 2003. Geo-ethnoarchaeology of pastoral sites: the identification of livestock enclosures in abandoned Maasai settlements. *Journal of Archaeological Science*, **30**(4), 439–459.

Shahack-Gross, R., Simons, A., and Ambrose, S. H., 2008. Identification of pastoral sites using stable nitrogen and carbon isotopes from bulk sediment samples: a case study in modern and archaeological pastoral settlements in Kenya. *Journal of Archaeological Science*, **35**(4), 983–990.

Simms, S. R., 1988. The archaeological structure of a bedouin camp. *Journal of Archaeological Science*, **15**(2), 197–211.

Cross-references

Analysis of Carbon, Nitrogen, pH, Phosphorus, and Carbonates as Tools in Geoarchaeological Research
Çatalhöyük
Ethnogeoarchaeology
Landscape Archaeology
Organic Residues
Paleodiet
Petrography
Site Formation Processes
Soil Micromorphology
Stable Carbon Isotopes in Soils
Tells
Trampling

PETROGLYPHS

Linea Sundstrom
Principal, Day Star Research, Shorewood, WI, USA

Synonyms

Abraded groove or tool-sharpening groove; Rock art; Rock carving; Rock etching; Rock imagery

Definition

Rock art is the general term for any human-generated modification to a rock surface, generally meaning engraving or painting. The term *petroglyph* is used for any rock art made by removing part of the rock surface to create an image or design, as opposed to *pictographs* or rock paintings, images, or designs made by adding pigment to the rock surface. Most researchers today include intentional, but nonpictorial, rock markings, such as abraded grooves, cupules, or so-called tally marks, in the petroglyph category; however, some place these and bedrock grinding surfaces into a separate archaeological feature category.

Introduction

Petroglyphs are intentional modifications to a rock surface made by removing part of the surface. Geoarchaeology enters petroglyph studies on several levels: (1) the type and structure of the rock surface, (2) the landform on which the modified rock surface occurs, and (3) the larger landscape context of the petroglyph site. These aspects of petroglyph geology contribute to the researcher's understanding of how, when, and why past people made and used petroglyphs.

Rock as medium

By definition, rock is the medium in which petroglyphs are made. The term refers only to works on immobile stone, not to such items as statuettes or incised tablets. Petroglyphs occur on cliffs, monoliths, horizontal bedrock exposures, boulders, and inside caves and rockshelters. Petroglyphs are found in almost all kinds of rock, but sandstone and basalt are the most common. In glaciated areas, petroglyphs are found on glacially smoothed beds of quartzite, limestone, and slate, as well as on boulder erratics. In short, petroglyphs occur on whatever suitably hard, smooth rock was available in a given area.

Though petroglyphs are made by removing parts of the rock surface, the amount of rock removed varies. On one end of the spectrum are those petroglyphs made by lightly scratching the rock surface to create relatively inconspicuous and short-lived marks. Others are more heavily incised into the surface, generally using an edged tool such as stone, bone knife, or graver. These techniques produce outlines formed of shallow cuts with a V- or U-shaped cross-section. Another common technique involves striking or pecking the rock with a hard object. The impact dents or craters the rock; a line of such dents makes up the outline of the design, and more dents may fill in all or part of a figure. Most pecked rock art has a "hill and valley" texture, with tiny circular or elliptical dents surrounded by unmodified rock. Depending on the angle at which the hammer strikes the rock, the tiny dents will be symmetrical or oblique in their cross-section. Fine, controlled lines are possible in pecked rock art through the use of indirect percussion (hammer and chisel). A small pointed stone or bone stylus is held in one hand with the point against the rock, while the butt of the implement is struck with a stone or bone hammer. This allows the artisan to produce precise outlines and silhouettes with even widths and depths. Pecking is frequently used to fill in the interior of figures in one of three ways: by solidly covering the space with overlapping peck marks, by filling in portions of the figure's interior with solid pecking, or by scattered pecks marks that do not overlap.

Either incised or pecked rock art designs can be further modified by rubbing the modified areas to smooth out the incisions or peck marks. This involves abrading the lines or silhouettes with a bone or stone tool to grind down the high points and create a smoother surface.

A third technique of petroglyph production is to grind away portions of a rock surface by direct abrasion with bone, stone, or wooden tools. A repeated back-and-forth movement typically results in a narrow, elliptical groove, deepest in the middle and tapering at the ends and sides. These banana-shaped grooves are sometime referred to as tool grooves or sharpening grooves. Multidirectional abrasion produces a shallow, dish-shaped feature, which sometimes serves as a "canvas" for additional petroglyph production. Circular ground areas, referred to as cupules, are another common form of petroglyph, formed by grinding pits into the rock surface. These occur on vertical as well as horizontal surfaces and sometimes cover the entire surface of a boulder or outcrop. The term pit-and-groove petroglyph is applied to these as well because, at many sites, the cupules are connected by incised or grooved lines. Related to abraded petroglyphs are images created by scraping away lichen or moss to create a design on a rock surface.

Recognizing petroglyphs

Because a petroglyph is made on rock and almost always remains within its natural setting, recognizing a petroglyph is often a matter of distinguishing human-generated features of the rock surface from natural ones. When a petroglyph is fresh, large, and in the shape of something complex, it is easy to recognize as rock art. Problems arise when petroglyphs are very lightly scratched into the rock surface, when they are worn down by erosion or remineralized to the same color as the larger rock surface, when calcite or silica accretions have built up over them, or when they are small or very simple in design. Merely as a consequence of human perception, highly visible petroglyphs tend to overshadow inconspicuous ones.

Another complicating factor is that the ancient petroglyph makers sometimes incorporated natural features of the rock surface into their petroglyphs. A slight bulge in the surface might become the rounded shape of an animal's back (Keyser and Poetschat, 2004). With the addition of a few extra lines, a natural crack or crevice might be transformed into a human or animal figure. An entire boulder might be carved to represent an animal, such as the so-called ribstones of the Canadian Great Plains (Wormington et al. 1965, 170–172). A columnar speleothem might be transformed into a humanlike creature by carving facial features into it (Stone, 2005).

It can be very difficult for even an experienced rock art researcher to decide whether a particular line is a petroglyph or a natural crack or scratch in the rock. In such cases, it may be necessary to apply lights from different angles or intensities or revisit the site at a different time of day. Petroglyphs that do not form complex designs or figures can be tricky to recognize. Further, petroglyphs that are simple and small are sometimes missed at sites where more complex, showy petroglyphs dominate. Abraded grooves and surfaces are often mistaken for natural features, and unusual natural features are often mistaken for petroglyphs by untrained observers. An experienced researcher, however, can usually make this distinction. If not, a geologist can advise as to whether the feature in question occurs naturally within the rock unit.

Geology of petroglyph distribution

In any distribution study of rock art, a first step is mapping the location of rock outcrops suitable for the kind of petroglyph under consideration (Chippendale and Nash 2004b, 10). Lithology factors into petroglyph distribution in several ways. First and most obviously, rock art is limited to areas that have, or previously had, exposed rock. Places without rock do not contain petroglyphs. In humid regions, petroglyph-bearing rock may have been subsequently covered by moss or buried by soil formation such that the formerly exposed rock faces now lie under a blanket of sod, peat, or vegetation. Thus, mapping rock outcrops may entail more than a simple snapshot of a currently visible outcrop. A second factor in petroglyph distribution concerns the durability of various kinds of rock. Very soft rock is not likely to preserve petroglyphs. Exposure to the elements and chemical and physical reactions to light, water, fire, and temperature affect the resistance of a given type of rock to granular deterioration and spalling. Third, lithology helps determine physical characteristics of a rock surface that may affect (1) whether it will be selected by a maker of petroglyphs and (2) the degree to which the carvings will be subject to erosion. Specifically, some kinds of rock are likely to form large horizontal "floors"; others are likely to contain crevices or caves; others contain springs or seeps. Finally, ancient peoples may have also selected rocks for other characteristics such as color, hardness, the sound produced by striking the rock, patterns of inclusions or interbedding, or whether striking the rock produces sparks.

Once the lithology of the area is mapped, the distribution of petroglyphs can then be mapped over it to see the degree to which the two correlate. Important caveats in any such studies are, first, that some rock art may not have survived to the present day and, second, that the study includes only areas for which complete geological and archaeological data are available (Hyder 2004, 92). In other words, a blank on the map should be demonstrably the result of the decisions of ancient people and not merely an artifact of a lack of survey there.

Geoarchaeology of petroglyph dating

Geoarchaeology contributes to attempts at dating petroglyphs in several ways. Perhaps the most direct involves dating sediments that cover all or part of a petroglyph to indicate a minimum age for the carving. Assuming that sediment gradually built up over the petroglyph, the age of the petroglyph must be greater than that of the sediment (Butzer et al., 1979, 1202; Loendorf, 1991). This dating technique requires careful analysis of the pattern of sedimentation and erosion. Deposits in sandstone rockshelters and below sandstone cliffs present special problems because the sediments are often extremely friable and unconsolidated. This can result in rapid, sporadic movement of sediment, rather than gradual buildup of stable surfaces and soils. Rock art sites frequently attract looters, and thus, the fill inside rockshelters or below cliffs may have been displaced by digging and the pits thus created quickly refilled with loose sand. It is, therefore, imperative that researchers carefully evaluate the integrity of datable material, such as charcoal, recovered while excavating. Another complicating factor is that these high energy depositional situations can undergo rapid alternations between erosion and sedimentation. The sediments covering a petroglyph today may represent the last of a series of cycles, rather than a long-term buildup that has been continuous since the petroglyph was made.

A less direct, geomorphic dating method involves reconstructing the history of alluvial terraces formed over or below petroglyphs, then determining the likely age of the terraces that would have been present when the petroglyphs were made. In some areas, petroglyphs are stranded high above the current ground surface. Reconstructing the terrace sequence could demonstrate that portions of the rock were formerly accessible from a terrace that had not yet been removed through erosion. The chronology of deposition and subsequent removal of that terrace provides a clue to the age of the petroglyphs, because the researcher can reasonably assume that the terrace was in place in order to provide access to the rock surface when the petroglyphs were made. The same would hold for a terrace that covers a petroglyph, with the assumption that the petroglyph was made before the stream deposited the sediments. Reconstructing the history of terrace formation is the first step in linking petroglyphs to the chronology of landscape development. The second step is dating discrete events in the process of alluvial feature formation. If a terrace contains datable material, such as organic-rich buried soils, estimated dates can be imposed on the timeline of terrace formation. The age of the petroglyph can then be estimated in relation to these events. This may be only a minimum or maximum age for the petroglyph, or it may be a range of time between two dated events.

For example, imagine a canyon cliff on which petroglyphs are stranded above the current ground surface. In many such instances, the only reasonable assumption is that the petroglyphs were made when the ground surface was higher than it is today and that the petroglyph-bearing portion of the cliff would then have been within easy reach or at least accessible by ladder. Reconstructing the terrace sequence and dates of terrace formation in the canyon can indicate the last time the petroglyphs could have been created – in other words, their minimum age. In another example, imagine a petroglyph low in the landscape that is now partially or completely covered by terrace sediments. Dating the terrace would again give a minimum age for the petroglyph, because it must have been made before the terrace formed. If the terrace is 4,000 years old, the petroglyph would have to be greater than 4,000 years old.

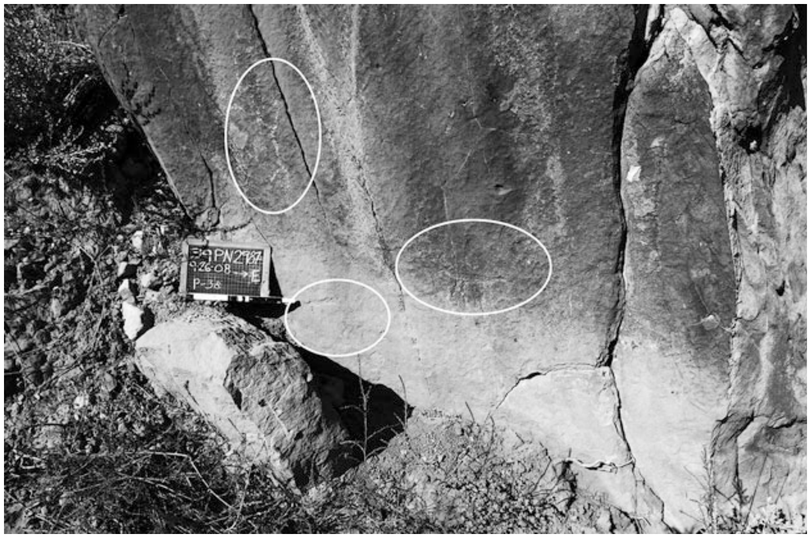
In the situation described above, petroglyphs high up on a rock face will be older than those farther down, because the terraces that provided access to the higher cliffs were removed by erosion after those petroglyphs were created. An opposite pattern would obtain, however, where sediments build up against a cliff, burying the lower petroglyphs and creating access to the higher portions of the rock face for the production of newer ones. A similar situation can occur when lateral dunes migrate along a cliff in arid areas. Petroglyphs in this situation will be covered and uncovered as dunes pass along the base of the cliff. If geomorphologists can estimate a rate of dune migration, this may provide a clue to the age of petroglyphs that show signs of having been made, then covered by dune deposits, then uncovered again by natural processes or archaeological excavation.

In formerly glaciated areas, petroglyphs incised into glacially scoured bedrock or made on glacial erratics are clearly younger in age than the glacial episode that formed or situated the surfaces on which the petroglyphs were made. Alluvial terraces formed on top of till or glacially scoured bedrock also must postdate the last glacial episode in the research area. Such terraces might cover petroglyphs made on bedrock – thus sandwiching the age of the rock art between the glacial retreat and formation of the terrace. Alternatively, such terraces might provide access to high cliffs that were out of reach just after the glacial episode but before the terrace sediments accumulated to a sufficient height to allow access for petroglyph creation on that section of the cliff face. In the former instance, the petroglyphs will be more recent than the glacial retreat that exposed the rock, but younger than the terrace that covers them. In the latter instance, the petroglyphs will postdate both the glacial episode and terrace formation. The more accurately the glaciation and terrace formation can be dated, the more securely the age of the petroglyphs can be estimated (Butzer et al., 1979, 1207–1209).

Weathering, lichens, and petroglyph dating

Though the degree of weathering on a petroglyph is an unreliable indicator of its calendar age (Dorn, 2001), comparison of weathering on petroglyphs of the same rock face or in very similar physical settings can indicate their relative ages. The apparent freshness of a petroglyph relies on three factors: (1) the degree of cortication (discussed in the following section), (2) the degree to which the indentations or incisions forming the design are rounded down by granular rock face deterioration or abrasion by agents such as animals or windborne sediments, and (3) whether or not the loose powdery rock residue created by pecking or incising the surface still adheres to the rock. The latter generally is lighter in color than the surrounding rock and thus makes the lines and shapes of the petroglyph stand out as if colored with white pigment.

Lichens vary widely in their rates of growth. Factors affecting this are species, the roughness and porosity of the rock surface, amount and angle of exposure to light, moisture, and the composition of the rock. Lichen dating has been applied to studies of alpine glaciations; however, its use in rock art dating has proved difficult because of the necessity for an independently verified calibration table and variability of growth rates in temperate zones (Jochimsen, 1973; Friedmann and Galun, 1974; Dorn, 2001, 173). The presence of lichens is no indicator of great age, as a visit to a modern cemetery will demonstrate. Nor does the absence of lichens mean a petroglyph is recent. Many rock surfaces do not provide a suitable habitat for lichens. Lichens colonizing a surface may be inadvertently removed by people tracing the petroglyph with their fingers. Further, petroglyphs may have been periodically renewed by removing moss or lichens or by recarving them along the original lines. Despite these limitations,



Petroglyphs, Figure 1 Petroglyph panel on sandstone, Black Hills, South Dakota, with pecked petroglyphs circled. The petroglyph at the *left* shows up better because the pecked lines cut through a darker surface cortex. The petroglyph at the *right* has reacquired its dark mineral and clay cortex so that it no longer stands out from the surrounding rock. The petroglyphs at the *bottom* were recently exposed by erosion of soil deposits from the base of the rock; here, neither the petroglyphs nor the surrounding rock has formed a cortex.

slow-growing lichen species may be reliable indicators of the relative ages of petroglyphs on a single rock surface or in a limited geographic area. In that instance, those petroglyphs that are partly or wholly obscured by lichens are older than those with no visible lichens on them. To make such comparisons, the rock art researcher will need to be familiar with the relative growth rates of various species in the area. Radiocarbon dating the lichen on a rock surface is not likely to succeed because the organisms comprising the lichen colony are still living.

Microstratigraphy and petroglyph dating

When two petroglyphs occur on the same rock surface, but one is corticated (covered by a dark crust or rind formed by ferromanganese compounds in a cemented skin of clay minerals) and the other uncorticated, the latter is obviously younger than the former. One has been exposed to the air long enough for the rock surface to reacquire the crust of oxidized iron or manganese that was removed when the petroglyph was created, while the other has been exposed to the air for a shorter time (Figure 1). Unfortunately, the rates at which these mineral rinds form vary widely according to the mineral content and porosity of the parent rock, as well as the climate regime in operation at the time of, and following, creation of the petroglyph (Butzer et al., 1979, 1202; Dorn, 2001). Comparing cortication rates on a single rock art panel thus may be helpful in determining the relative ages of elements on it – assuming that all carvings receive roughly the same amount of moisture and sunlight – but less reliable in estimating calendar ages for the rock art. Researchers have sought to expand the usefulness of this method of petroglyph dating by quantifying rates of formation for the mineral crusts or cortexes (Dorn and Whitley, 1984; Nobbs and Dorn, 1988; Dorn, 1983; Francis et al., 1993; Whitley and Annegarn, 1994). Referred to as cation-ratio dating, this method measures the ratios of cations of various elements such as potassium, calcium, and titanium in small samples of the mineral crust to quantify the degree of recortication since the petroglyph was first cut into the rock surface. Large numbers of these ratios are then combined to form a cation-ratio curve that represents the change in ratios over time. These rates of change must be calibrated to rock surfaces in the same region for which ages have been determined through some independent means (Dorn, 1989). Calibration has proved difficult, and the method has further been limited by variability in cation ratios across individual layers of encrustation (Watchman, 2000; Smith et al., 2009; Brook et al., 2011).

Deposits of calcite or silica can also form part of the microstratigraphy of a rock art panel. In limestones and dolomites, calcite compounds dissolve from the rock and redeposit as translucent skins. As these calcite deposits build up, the rock art they cover becomes less distinct. In equable climates, these deposits may build up as regular, uniform layers, with each layer representing a single year's wet season. In places subject to less regular moisture regimes, the layers may form only in wet years or only during wet climatic episodes, and their thickness may vary year to year and with the duration of climatic episodes, similar to tree rings. Although not widely used, calcium carbonate and calcium oxalate skins can be dated by radiocarbon or uranium-series methods to give a minimum age for the petroglyphs they cover (Smith and Turner, 1975;

Dragovich, 1986; Watchman, 2000; Bednarik, 2002; Aubert et al., 2007). Petroglyphs in granite, sandstone, diabase, gneiss, and mica schists can similarly build up deposits of silica. This process is the beginning of cortication and involves iron and manganese compounds cemented by clay minerals to form a transparent skin on the rock surface (Butzer et al., 1979, 1211, n. 6).

Since moisture is a factor in the formation of silicate and calcite deposits, these microstrata, as seen in a thin section of the rock surface, may serve as climate indicators. Generally speaking, dry conditions favor the formation of orange, manganese-poor crusts, and wet conditions favor black, manganese-rich crusts (Liu and Dorn 1996). In regions with pronounced climate fluctuations, the pattern of climate shifts thus revealed may aid in pinning the microstrata and the rock art they superpose to calendar dates (Liu et al., 2000; Zhou et al., 2000).

While researchers have successfully applied radiocarbon dating to pigments, this method is not yet reliable for petroglyphs. Since making a petroglyph does not involve organic carbon compounds, such dates would instead measure the age of a subsequent event, such as formation of a mineral crust over the petroglyph (Chippendale and Nash 2004b, 5). Experiments in dating microscopic organics, such as bacteria, trapped under a calcite or silica skin have thus far proved contradictory and not replicable (Dorn, 1996, 2001; Beck et al., 1998; Dragovich, 2000; Watchman, 2000). Two problems have hindered this method: current radiocarbon dating methods require much larger samples than the very minute amounts of organic material trapped between mineral skins, and formation of such organics does not reliably represent a single event, but may compound periods of bacterial growth separated by hundreds or thousands of years (Beck et al., 1998; Dragovich, 2000; Dorn, 2001; Brook et al., 2011). Better results were obtained at Rhino Cave in the Kalahari Desert, where mineral crusts and interbedded organics formed much thicker layers (Brook et al., 2011). Besides obtaining a consistent column of radiocarbon age estimates, Brook et al. (2011) argue that a shift from phosphate to carbonate and then to silica between the base and surface of the coating indicates a gradual trend toward a drier climate in the late Holocene.

Paleontology, ecology, and petroglyph dating

Convincing depictions of extinct or locally extinct species have long been considered a clue to the age of petroglyphs. The great cave art traditions of the European Upper Paleolithic are the best known example of dating ancient art by the species it depicts. Other regions also contain rock art representing Middle and Late Pleistocene fauna (Butzer et al., 1979, 1206). While this method of age estimation seems straightforward, it has its limits. First, it can indicate only a minimum age for the rock art, which presumably was made before the animal went extinct. Second, the human ability to carry information through time and across space may have allowed an extinct species to be pictured in places outside its actual habitat or long after it disappeared locally or altogether. A third limit to using this method is the ability of the researcher to recognize what animal the ancient artist intended, if any. All cultures seem to invoke notions of mythic creatures that combine features of various species, such as the dragon of Asian and European tradition. Fossils, vision experiences, and the human imagination are capable of suggesting the appearance and behavior of living things that do not exist in the real world. And even if an actual living species was intended, researchers may not understand the reference. For example, two petroglyphs on a petroglyph panel in Utah have recently been put forth as depictions of Columbian mammoths (Malotki and Wallace, 2011). The petroglyphs actually match more closely the form of the tobacco moth than that of a mammoth, however. The purported mammoth trunk may be the proboscis of the moth, and the "tusks" may be the moth's antennae. Although one is a huge, and the other a tiny, animal, nothing on the panel provides scale.

At the same time, a rock art style that contains depictions of a wide variety of animals should include species consistent with the age proposed for it. Pleistocene-aged petroglyphs can be expected to include Pleistocene species. The absence of extinct Pleistocene species where modern species are depicted argues for a post-Pleistocene age for the body of rock art.

Similarly, the presence of introduced or domesticated species also limits the potential age of petroglyphs. In Native American rock art, depictions of horses date petroglyphs to the post-Columbian era. In South Africa, petroglyphs of domesticated sheep and cattle are also known to date to the last few centuries (Butzer et al., 1979, 1207). In Australia, depictions of horses, pigs, cattle, and water buffalo postdate the mid-nineteenth century (Chippindale and Taçon 1998, 95).

To the extent that species depicted in rock art indicate a specific environment, petroglyphs can be tied to paleoecological sequences derived from other data. In northern Australia's Arnhem Land, pictures of riverine and marshland species mark the progress of rising sea levels during the postglacial era, and they indicate local shifts from saltwater estuarine to freshwater riverine species (Taçon 1988; Chaloupka, 1993; Chippindale and Taçon, 1998). In Scandinavia, the distribution of petroglyphs in coastal areas has been correlated to shifting postglacial sea levels (Helskog, 1999).

Geoarchaeology of petroglyph preservation

Petroglyphs present preservation issues different from those of other historic and archaeological sites. On the positive side, the difficulty of moving petroglyphs means they are more likely than other kinds of archaeological remains to retain their physical context (Chippendale and Nash 2004b). Petroglyphs are so embedded in their landscape that removing them takes extraordinary effort. On the negative side, the surrounding environment can be subject to extensive damage. For example, the city of Albuquerque, New Mexico, has expanded to the edges of, and around, Petroglyph National Park. In other areas, the exposed and visible nature of petroglyphs has attracted people to sites, with concomitant increase in graffiti and unintentional damage to the rock art. The open, exposed nature of petroglyphs also makes them vulnerable to various forms of physical and chemical alteration that would not occur to buried archaeological materials. Because petroglyphs are incorporated into a rock surface, they are subject to the same physical and chemical deterioration as the rock itself.

Any attempt to mitigate damage to petroglyphs requires an assessment of their physical setting at various scales, from their macroenvironment to the mineralogy of the rock surface (Watchman, 1992; Thorn and Dean, 1995; Loubser, 2001). Physical damage to petroglyphs can operate on the scale of complete loss of the rock surface on which the petroglyphs occur to damage on the microscopic level, including everything in between. Large-scale damage to rock art surfaces occurs in three main ways: seismic activity, cliff and rockshelter collapse, and mass wasting of hillslopes resulting in displacement or burial of rock surfaces and monoliths. Blocks of fallen cliff frequently migrate downslope. This can result in petroglyphs being buried on the downside of the block or subsequently buried by sediment piling up against the rock. The openings to caves containing rock art can be sealed by large-scale sediment movement.

Cliffs collapse for two reasons. First, if the bedrock has a blocky structure, sediment and water can build up in fissures. Ongoing freeze-thaw cycles then result in expansion of fissures and calving off of blocks of the cliff. Climate patterns affect this, in that wet years and wet climate periods tend to encourage this process. The second way cliffs fail is when resistant, relatively heavy strata overlie weak strata. The lower strata erode more rapidly than the higher ones, leading to undermining of cliffs. This creates rockshelters that may attract human habitation and petroglyph production. A cave or rockshelter formed in this way can eventually collapse under its own weight as the underlying strata are further eroded.

On a smaller scale, petroglyphs can be damaged or lost if a small portion of a cliff surface breaks off. Sometimes this involves the lower edge of a cliff or a protruding aspect of the rock. More commonly, the underlying rock remains intact, but the outer layer spalls off, taking part or all of a petroglyph with it. The extent and timing of this process depends on the underlying rock type, the nature of any mineral rind that forms on the surface of the cliff, rock porosity, and exposure to freeze-thaw and to wildfires. A heavy, nonporous mineral crust on the outside of a relatively porous cliff allows the buildup of moisture behind the crust. As this moisture expands and freezes, it exerts pressure on the crust, causing it to spall or flake.

Soft and grainy rock is subject to erosion at the microscopic level. Sandstones and quartzites were often selected for petroglyphs. These rocks vary widely in grain sizes, angularity of grains, and in the hardness of the matrix (often silica) that cements the grains together. Some sandstones are so soft that just brushing against them removes the loosely cemented particles. On the other end of the spectrum, some quartzites and basalts are so hard that one must apply considerable force to chip away a small portion of rock.

Geology and rock art interpretation

Archaeologists are increasingly recognizing the importance of physical setting in attempts to understand the meaning and significance of ancient rock art (e.g., Deacon, 1988; Taçon, 1990; Bradley, 1997; Hartley and Vawser, 1998; Helskog, 1999; Arsenault, 2004a, b; Chippindale and Nash 2004a, b; Hyder, 2004; Taçon, 2010; Norder, 2012). Geological features may have been imbued with special meaning if they were unusual; visually striking; sources of tool stone, pigments, or other scarce resources; or evocative of faces, animals, or shelters. Such places are likely to contain petroglyphs that reflect their importance in indigenous geographies (Arsenault, 2004b; Flood, 2004, 194–195). Unique geological features, such as "drum rocks" (hollow rocks that produce drumlike sounds when struck), rocks with echoes, and rocks that align to astronomical cycles – such as winter solstice or seasonal appearances of particular stars – and high and low points in the landscape are likely to be important landmarks in indigenous geographies (Ouzman, 2001; Goldhahn, 2002; Rainbird, 2002; Loendorf, 2004; Waller and Arsenault, 2008; Lahelma, 2010; Hultman, 2010). Passes and other places that facilitate travel also attracted rock art (Wallace and Holmlund, 1986, 138–141; Hedges and Hamann, 1992; Bradley, 1997, 214). Placement of petroglyphs and other rock art is not simply a matter of finding a flat, smooth surface, as any rock art researcher can attest. Sometimes a place of purported supernatural power will contain numerous petroglyphs – even in locations that are rough, hard to access, hard to see, or already covered with rock art – while other wide open cliffs will contain no rock art at all. Some rock art was meant to be seen, and some was meant to be hidden. Sometimes the sounds of ceremonies, including the sounds produced by making or renewing petroglyphs, were meant to be within earshot of a village or ceremonial ground. The scale at which archaeologists consider environment will vary according to the data available and the research questions. In analyzing a body of petroglyphs, "environment" can mean the position of the rock art within a site, the position of the site within a local setting, or the local setting within a regional environment (Butzer, 1982, 38).

A particular contribution of geoarchaeology to this aspect of rock art research is its methods of reconstructing past landscapes and geological features. As noted above, in alluvial settings, such as canyons, surface elevations may have changed dramatically since the petroglyphs were made, and so the archaeologist needs an accurate picture of the place at the time the rock art was produced. In the same way, a sense of the fluvial and biological settings is also important to such contextual studies. Was the area treeless when the petroglyphs were carved, or did brush and trees hide the rock surface from sight? Did water run across the rock after a storm or during the spring thaw? Were there seeps and springs along geological contacts that no longer flow today? Has a rockshelter collapsed, hiding rock art panels behind the resulting rubble cone? Has the hillslope below a panel eroded to the point of making the petroglyphs impossible to reach today? Has movement of terrace or dune deposits completely obscured some rock art panels? Have some panels been lost to mass wasting or micro-erosion? These possibilities need to be addressed in any interpretations that rest on distributional data, because the current dispersal pattern of panels may be quite different from that of ancient times.

Summary

Geoarchaeology contributes to petroglyph studies by providing contextual information important to estimating the age of the rock art and sometimes its meaning, as well. A petroglyph site can be said to have two environmental settings: the current one and the one in place when the petroglyphs were made. These may be the same or distinctly different, depending on the age of the petroglyphs and the rate at which natural or human forces have modified the landscape. The manner in which ancient peoples placed petroglyphs within their effective environment reflects their particular cultural beliefs about landscape. Research into such ancient geographies obviously relies on the methods of geomorphology to reconstruct an accurate picture of the past form of the landscape, stream courses, passes, and the distribution of important natural resources. Each site also has its own distinctive setting, which again is best approached through reconstruction of former landscapes. On an even closer level, the rock surface itself is a microenvironment. The exposed rock into which petroglyphs were engraved, pounded, or ground is a complex interface between the parent rock, water, air, microorganisms, lichens, and the forces of wind, sunlight, precipitation, and fluctuating temperatures. Various methods have been developed for obtaining age estimates from the microscopic stratigraphy of petroglyphs.

Bibliography

Arsenault, D., 2004a. Rock-art, landscape, sacred places: attitudes in contemporary archaeological theory. In Chippindale, C., and Nash, G. (eds.), *The Figured Landscapes of Rock-Art: Looking at Pictures in Place*. Cambridge, UK: Cambridge University Press, pp. 69–84.

Arsenault, D., 2004b. From natural settings to spiritual places in the Algonkian sacred landscape: an archaeological, ethnohistorical, and ethnographic analysis of Canadian Shield rock-art sites. In Chippindale, C., and Nash, G. (eds.), *The Figured Landscapes of Rock-Art: Looking at Pictures in Place*. Cambridge, UK: Cambridge University Press, pp. 289–317.

Aubert, M., O'Connor, S., McColloch, M., Mortimer, G., Watchman, A., and Richer-LaFlèche, M., 2007. Uranium-series dating rock art in East Timor. *Journal of Archaeological Science*, **34**(6), 991–996.

Beck, W., Donahue, D. J., Jull, A. J. T., Burr, G., Broecker, W. S., Bonani, G., Hajdas, I., and Malotki, E., 1998. Ambiguities in direct dating of rock surfaces using radiocarbon measurements. *Science*, **280**(5372), 2132–2139.

Bednarik, R. G., 2002. The dating of rock art: a critique. *Journal of Archaeological Science*, **29**(11), 1213–1233.

Bradley, R., 1997. *Rock Art and the Prehistory of Atlantic Europe: Signing the Land*. London: Routledge.

Brook, G. A., Railsback, L. B., Campbell, A. C., Robbins, L. H., Murphy, M. L., Hodgins, G., and McHugh, J., 2011. Radiocarbon ages for coatings on cupules ground in quartzite bedrock at Rhine Cave in the Kalahari Desert of Botswana, and the paleoclimatic significance. *Geoarchaeology*, **26**(1), 61–82.

Butzer, K. W., 1982. *Archaeology as Human Ecology: Method and Theory for a Contextual Approach*. Cambridge, UK: Cambridge University Press.

Butzer, K. W., Fock, G. J., Scott, L., and Stuckenrath, R., 1979. Dating and context of rock engravings in southern Africa. *Science*, **203**(4386), 1201–1214.

Chaloupka, G., 1993. *Journey in Time: The World's Longest Continuing Art Tradition*. Chatswood: Reed.

Chippendale, C., and Nash, G., 2004a. Pictures in place: approaches to the figured landscapes of rock-art. In Chippindale, C., and Nash, G. (eds.), *The Figured Landscapes of Rock-Art: Looking at Pictures in Place*. Cambridge, UK: Cambridge University Press, pp. 1–36.

Chippindale, C., and Nash, G. (eds.), 2004b. *The Figured Landscapes of Rock-Art: Looking at Pictures in Place*. Cambridge, UK: Cambridge University Press.

Chippindale, C., and Taçon, P. S. C., 1998. The many ways of dating Arnhem Land rock-art, North Australia. In Chippindale, C., and Taçon, P. S. C. (eds.), *The Archaeology of Rock-Art*. Cambridge, UK: Cambridge University Press, pp. 90–111.

Deacon, J., 1988. The power of a place in understanding southern San rock engravings. *World Archaeology*, **20**(1), 129–140.

Dorn, R. I., 1983. Cation-ratio dating: a new rock varnish age-determination technique. *Quaternary Research*, **20**(1), 49–73.

Dorn, R. I., 1989. Cation-ratio dating of rock varnish: a geographic assessment. *Progress in Physical Geography*, **13**(4), 559–596.

Dorn, R. I., 1996. A change of perception. *La Pintura*, **23**(2), 10–11.

Dorn, R. I., 2001. Chronometric techniques: engravings. In Whitley, D. S. (ed.), *Handbook of Rock Art Research*. Walnut Creek: Altamira, pp. 167–189.

Dorn, R. I., 2009. Desert rock coatings. In Parsons, A. J., and Abrahams, A. D. (eds.), *Geomorphology of Desert Environments*, 2nd edn. New York: Springer, pp. 153–186.

Dorn, R. I., and Whitley, D. S., 1984. Chronometric and relative age determination of petroglyphs in the western United States. *Annals of the Association of American Geographers*, **74**(2), 308–322.

Dragovich, D., 1986. Minimum age of some desert varnish near Broken Hill, New South Wales. *Search*, **17**(5–6), 149–151.

Dragovich, D., 2000. Rock engraving chronologies and accelerator mass spectrometry radiocarbon age of desert varnish. *Journal of Archaeological Science*, **27**(10), 871–876.

Flood, J., 2004. Linkage between rock-art and landscape in Aboriginal Australia. In Chippindale, C., and Nash, G. (eds.), *The Figured Landscapes of Rock-Art: Looking at Pictures in Place*. Cambridge, UK: Cambridge University Press, pp. 182–200.

Francis, J. E., Loendorf, L. L., and Dorn, R. I., 1993. AMS radiocarbon and cation-ratio dating of rock art in the Bighorn Basin of Wyoming and Montana. *American Antiquity*, **58**(4), 711–737.

Friedmann, E. I., and Galun, M., 1974. Desert algae, lichen, and fungi. In Brown, G. W. J. (ed.), *Desert Biology*. New York: Academic, pp. 165–212.

Goldhahn, J., 2002. Roaring rocks: an audio-visual perspective on hunter-gatherer engravings in northern Sweden and Scandinavia. *Norwegian Archaeological Review*, **35**(1), 29–61.

Hartley, R., and Vawser, A. M. W., 1998. Spatial behaviour and learning in the prehistoric environment of the Colorado River drainage (south-eastern Utah), western North America. In Chippindale, C., and Taçon, P. S. C. (eds.), *The Archaeology of Rock-Art*. Cambridge, UK: Cambridge University Press, pp. 185–211.

Hedges, K., and Hamann, D., 1992. Look to the mountaintop: rock art at Texas Hill, Arizona. In Weaver, D. E., Jr. (ed.), *American Indian Rock Art*. El Toro: American Rock Art Research Association, Vol. 17, pp. 44–55.

Helskog, K., 1999. The shore connection. Cognitive landscape and communication with rock carvings in northernmost Europe. *Norwegian Archaeological Review*, **32**(2), 73–94.

Hultman, M., 2010. Known yet unknown ringing stones of Sweden. In Goldhahn, J., Fuglestvedt, I., and Jones, A. (eds.), *Changing Pictures: Rock Art Traditions and Visions in Northern Europe*. Oxford: Oxbow, pp. 60–72.

Hyder, W. D., 2004. Locational analysis in rock-art studies. In Chippindale, C., and Nash, G. (eds.), *The Figured Landscapes of Rock-Art: Looking at Pictures in Place*. Cambridge, UK: Cambridge University Press, pp. 85–101.

Jochimsen, M., 1973. Does the size of lichen thalli really constitute a valid measure for dating glacial deposits? *Arctic and Alpine Research*, **5**(4), 417–424.

Keyser, J. D., and Poetschat, G., 2004. The canvas as the art: landscape analysis of the rock-art panel. In Chippindale, C., and Nash, G. (eds.), *The Figured Landscapes of Rock-Art: Looking at Pictures in Place*. Cambridge, UK: Cambridge University Press, pp. 118–130.

Lahelma, A., 2010. Hearing and touching rock art: Finnish rock paintings and the non-visual. In Goldhahn, J., Fuglestvedt, I., and Jones, A. (eds.), *Changing Pictures: Rock Art Traditions and Visions in Northern Europe*. Oxford: Oxbow, pp. 48–59.

Liu, T., and Dorn, R. I., 1996. Understanding the spatial variability of environmental change in drylands with rock varnish microlaminations. *Annals of the Association of American Geographers*, **86**(2), 187–212.

Liu, T., Broecker, W. S., Bell, J. W., and Mandeville, C. W., 2000. Terminal Pleistocene wet event recorded in rock varnish from the Las Vegas Valley, southern Nevada. *Palaeogeography Palaeoclimatology Palaeoecology*, **161**(3–4), 423–433.

Loendorf, L. L., 1991. Cation-ratio varnish dating and petroglyph chronology in southeastern Colorado. *Antiquity*, **65**(247), 246–255.

Loendorf, L. L., 2004. Places of power: the placement of Dinwoody petroglyphs across the Wyoming landscape. In Chippindale, C., and Nash, G. (eds.), *The Figured Landscapes of Rock-Art: Looking at Pictures in Place*. Cambridge, UK: Cambridge University Press, pp. 201–216.

Loubser, J., 2001. Management planning for conservation. In Whitley, D. S. (ed.), *Handbook of Rock Art Research*. Walnut Creek: Altamira, pp. 80–115.

Malotki, E., and Wallace, H. D., 2011. Columbian mammoth petroglyphs from the San Juan River Basin near Bluff, Utah, United States. *Rock Art Research*, **28**(2), 143–152.

Nobbs, M., and Dorn, R. I., 1988. Age determinations for rock varnish formation within petroglyphs: cation-ratio dating of 24 motifs from the Olary region, South Australia. *Rock Art Research*, **5**(2), 108–146.

Norder, J., 2012. Landscapes of memory and presence in the Canadian Shield. In Sundstrom, L., and DeBoer, W. (eds.), *Enduring Motives: The Archaeology of Tradition and Religion in Native America*. Tuscaloosa: University of Alabama Press, pp. 361–381.

Ouzman, S., 2001. Seeing is deceiving: rock art and the non-visual. *World Archaeology*, **33**(2), 237–256.

Rainbird, P., 2002. Making sense of petroglyphs: the sound of rock-art. In David, B., and Wilson, M. (eds.), *Inscribed Landscapes: Marking and Making Place*. Honolulu: University of Hawaii Press, pp. 93–103.

Smith, G. A., and Turner, W. G., 1975. *Indian Rock Art of Southern California with Selected Petroglyph Catalog*. Redlands: San Bernardino County Museum Association.

Smith, M. A., Watchman, A., and Ross, J., 2009. Direct dating indicates a mid-Holocene age for archaic rock engravings in arid central Australia. *Geoarchaeology*, **24**(2), 191–203.

Stone, A., 2005. Divine stalagmites: modified speleothems in Maya caves and aesthetic variation in Classic Maya art. In Heyd, T., and Clegg, J. (eds.), *Aesthetics and Rock Art*. Aldershot: Ashgate Publishing, pp. 215–234.

Sundstrom, L., 2004. *Storied Stone: Indian Rock Art of the Black Hills Country*. Norman: University of Oklahoma Press.

Taçon, P. S. C., 1988. Identifying fish species in the recent rock paintings of western Arnhem Land. *Rock Art Research*, **5**(1), 3–15.

Taçon, P. S. C., 1990. The power of place: cross-cultural responses to natural and cultural landscapes of stone and earth. In Vastokas, J. M., Paper, J. D., and Taçon, P. S. C. (eds.), *Perspectives of Canadian Landscapes: Native Traditions*. North York: Robarts Centre for Canadian Studies, York University, pp. 11–43.

Taçon, P. S. C., 2010. Identifying ancient landscapes in Australia: from physical to social. In Preucel, R. W., and Mrozowski, S. A. (eds.), *Contemporary Archaeology in Theory: The New Pragmatism*, 2nd edn. Chichester: Wiley-Blackwell, pp. 77–91.

Thorn, A., and Dean, C., 1995. Condition surveys: an essential management strategy. In Ward, G. K., and Ward, L. A. (eds.), *Management of Rock Imagery*. Melbourne: Australian Rock Art Research Association. Occasional Publication, Vol. 9, pp. 116–123.

Wallace, H. D., and Holmlund, J. P., 1986. *Petroglyphs of the Picacho Mountains, South Central Arizona*. Goleta: Institute for American Research.

Waller, S. J., and Arsenault, D., 2008. Echo spirits who paint rocks: Memegwashio dwell within Echoing Rock Art Site EiGf-2. *American Indian Rock Art*, **34**, 191–201.

Watchman, A., 1992. Repainting or periodic-painting at Australian Aboriginal sites: evidence from rock surface crusts. In Ward, G. K. (ed.), *Retouch: Maintenance and Conservation of Aboriginal Rock Imagery*. Melbourne: Australian Rock Art Research Association. Occasional Publication, Vol. 5, pp. 26–31.

Watchman, A., 1996. A review of the theory and assumptions in the AMS dating of the Foz Côa petroglyphs, Portugal. *Rock Art Research*, **13**(1), 21–30.

Watchman, A., 2000. Micro-excavation and laser extraction methods for dating carbon in silica skins and oxalate crusts. In Ward, G. K., and Tuniz, C. (eds.), *Advances in Dating Australian Rock-Markings*. Melbourne: Australian Rock Art Association. Occasional Publication, Vol. 10, pp. 35–39.

Whitley, D. S., and Annegarn, H. J., 1994. Cation-ratio dating of rock engravings from Klipfontein, northern Cape Province, South Africa. In Dowson, T. A., and Lewis-Williams, J. D. (eds.), *Contested Images: Diversity in Southern African Rock Art Research*. Johannesburg: University of Witwatersrand Press, pp. 189–197.

Wormington, H. M., Forbis, R. G., and Griffin, J. B., 1965. *An introduction to the archaeology of Alberta, Canada*. Proceedings of the Denver Museum of Natural History, Denver, Colordo. 11.

Zhou, B. G., Liu, T., and Zhang, Y. M., 2000. Rock varnish microlaminations from northern Tianshan, Xinjiang and their paleoclimatic implications. *Chinese Science Bulletin*, **45**(4), 372–376.

Cross-references

Cave Settings
Climatostratigraphy
Landscape Archaeology
Paleoenvironmental Reconstruction
Pigments
Rockshelter Settings
Sedimentology
Site Preservation
Speleothems
X-ray Fluorescence (XRF) Spectrometry in Geoarchaeology

PETROGRAPHY

Ian K. Whitbread
School of Archaeology and Ancient History, University of Leicester, Leicester, UK

Definition

Petrography. The systematic description of geological materials, their composition, and organization, in hand specimens and thin sections.

Petrology. Study of the origin, structure, and composition of rocks.

Ceramic petrology. The interpretation of raw materials selection, ceramic technology, and provenance determination based upon the results of petrographic investigations.

Introduction

Geological materials such as the various types of igneous, metamorphic, and sedimentary rocks are diverse in both composition and structure. These properties have been distinguished and repeatedly exploited by people in the past based on their own culturally specific interpretations of the natural world. Petrography includes key analytical techniques used in modern science for identifying and characterizing rocks and sediments based on their mineralogical compositions and structures. It has many archaeological applications as diverse as regional landscape studies, site formation processes, raw materials exploitation, building construction, and the fabrication of artifacts such as stone tools and pottery.

Petrography incorporates two analytical procedures based on the nature of the analyzed surface and the instrumentation used. *Hand specimen analysis* of minerals and rocks requires no more than a freshly broken surface and is accomplished using the unaided eye (macroscopic observation), a hand lens (approximately 10×), or stereomicroscope (typically 10–200×) to improve visibility. *Thin section analysis* requires the laboratory preparation of samples for study under a transmitted light polarizing microscope (approximately 20–600×) enabling much greater accuracy and precision in determining mineral compositions and examining microstructures.

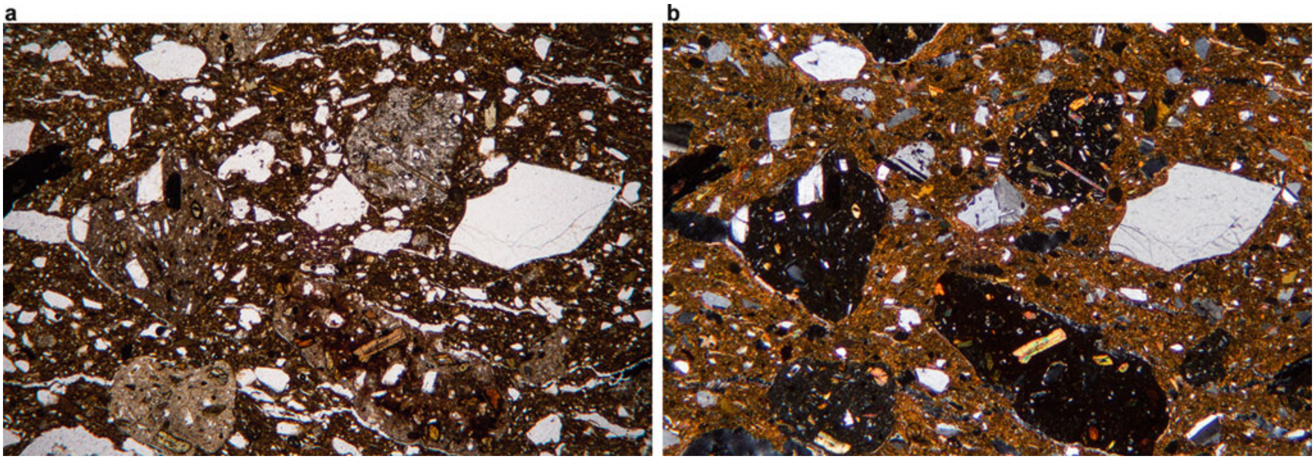
Petrography is a mature technique that bridges the divide between field and laboratory studies. It is often used in conjunction with instrumentally more advanced methods of materials analysis, such as chemical analysis (e.g., NAA, ICP-MS) and scanning electron microscopy (SEM), and it continues to be a widely applicable and cost-effective technique, most importantly because it addresses visually observable properties at both macro- and microscopic scales. Indeed, at these scales, compositional and structural markers, such as lustrous inclusions and grain size, may be recognizable with the unaided eye or through touch and therefore potentially noticeable or intended by people in the past. Another advantage of petrography is that the rocks and minerals identified can be further explored through geological literature and maps for the region under study, both of which are significant aids in studying raw material procurement patterns and the provenance of artifacts. Basic petrographic skills can be learned relatively easily by nonspecialists, but considerable experience is necessary when researching complex geological materials or difficult archaeological problems.

Hand specimen petrography

Hand specimens are routinely studied during fieldwork for rapid on-site characterization of rocks and minerals. Rocks are described on the basis of their composition (types and quantities of constituents), texture (overall appearance in terms of the size, shape, sorting, intergranular relationships, and orientations), and color. Minerals within a rock are usually identified by means of their form and habit, cleavage and fracture, twinning, hardness, specific gravity, color, streak, and luster (Dietrich and Skinner, 1979). Hand specimen studies may be the only means of analysis available if samples cannot be removed from their location of origin or destructively sampled, as in the examination of architectural components and precious objects. Where samples can be taken for further analysis, the selection procedure often starts by taking account of variation identified in hand specimen study. This procedure is equally valuable in reverse. Where results from the laboratory study of a few thin sections can be expressed in terms of characteristic macroscopic features, then hand specimen techniques can be used to identify these materials within regional landscapes or the substantial assemblages of artifacts found through excavation.

Thin section petrography

Petrography usually refers to the microscopic analysis of thin sections. Microscopic analysis of rock thin sections



Petrography, Figure 1 Thin section of Neolithic coarse ware (sample 73) from the Cave of Euripides, Salamis, Greece. The fabric contains volcanic inclusions consistent with a source on the neighboring island of Aegina (Whitbread and Mari, 2014). Width of the field = 4.6 mm, (**a**) plane-polarized light, (**b**) crossed-polarized light.

was pioneered by Henry Clifton Sorby in 1849, followed shortly by its first application to archaeological material with Sorby's 1869 attribution of rocks found in excavations at Frilford, Oxfordshire, United Kingdom, to volcanic sources at Niedermendig in the Eifel Mountains, Germany (Worley, 2009). From this beginning, petrography has been widely applied within geoarchaeology, principally in the study of worked stone, pottery, and soils, but also for specialized materials such as plaster (Goren and Goldberg, 1991; Karkanas, 2007), mortar (Hughes and Cuthbert, 2000; Pavía and Caro, 2008), and concrete (St John et al., 1998; Oleson et al., 2004; Walsh, 2007; Vola et al., 2011).

To make a thin section of soft materials, such as sediments, soils, or poorly fired pottery, they first need to be consolidated with an impregnating medium, such as an epoxy resin. Thin sections are then prepared by grinding a flat surface on the sample and bonding it to a glass slide (measuring either 75 × 25 mm or 46× 27 mm). The mounted sample is then ground to a standard thickness, usually 0.03 mm, at which point it either receives a concluding fine polish or is protected by attachment of a glass coverslip (Nesse, 2004). At this thickness (30 µm), many common minerals are translucent and can be identified by optical effects when light is refracted through them.

Thin sections must be studied using a polarizing (or petrological) microscope (Kile, 2003). The thin section is placed on a rotating stage above the microscope light source. Light reaching the thin section is polarized by a filter (the polarizer) beneath the stage so that it vibrates in one direction only. This light is refracted as it passes through most minerals in the thin section. A second polarizing filter is situated above the sample, between the microscope objective lens and eyepiece. This filter (the analyzer) is set at 90° to the polarizing filter below the stage but it can be moved in and out of the light path. When the analyzer is inserted into the light path with no sample on the stage, it blocks out all light from the polarizer so that the observer sees only darkness. With a mineral sample on the stage, transmitted light is refracted, and in most cases, the vibration direction is split and twisted slightly (double refraction) so that the analyzer does not cancel out all the light.

Examination of the thin section takes place under two types of illumination, plane-polarized light (analyzer removed) (Figure 1a) and crossed-polarized light (analyzer inserted) (Figure 1b). Minerals in the thin section can be identified from their optical properties, some of which need to be determined by using the rotating stage to align minerals with the polarizing filters. The properties studied in plane-polarized light include color and changes in color on rotation (pleochroism), form and habit, cleavage, and refractive index. Most rock-forming minerals are optically anisotropic in that they have different optical properties in different orientations of the mineral. Under crossed polarizers, the property of double refraction in these minerals interferes with the light path to cause a spectrum of artificially produced colors (interference colors). The maximum interference colors and angles at which they are extinguished on sample rotation are distinctive properties for mineral identification.

Lithic petrography

The geological materials most suited to petrographic analysis are coarse-grained rocks, especially those with discrete distribution patterns within the landscape so that an analyzed sample can be traced to its likely area of origin. For example, sedimentary rocks such as sandstone or limestone are often employed as building stone because they are widely available and easily worked. Petrography can be used to identify the selective use of particular types of stone for construction, but in the case of limestone and sandstone, it may be difficult to track examined samples to specific sedimentary deposits within a landscape where similar material is the dominant rock. Even where petrographically distinctive sedimentary rocks can be isolated, the distribution of sedimentary formations is usually extensive, and this makes it challenging to identify a specific locality from which the material was quarried. Materials such as marble and limestone are now sourced more effectively using chemical techniques if visual or structural peculiarities do not identify them unequivocally (see Herz and Waelkens, 1988; Olson, 2011). By contrast, igneous rocks often occur as discrete outcrops or locations in the terrain and are therefore more amenable to provenance determination. As a further example, during the Neolithic period in Britain, ground stone axes were produced in considerable numbers from various discrete igneous and related sources and transported across the country through extensive exchange networks. A major program of petrographic analysis has identified many of these sources and attributed individual axes to their respective origins throughout the country (Clough and Woolley, 1985). Extensive sampling has produced a substantial data set and numerous distribution patterns, but petrography on its own cannot address the many archaeological questions concerning how and why stone axes were produced and distributed. This study demonstrates very clearly the role of petrography as an analytical tool, but also the necessary interdisciplinary nature of geoarchaeological research in order to achieve archaeologically meaningful interpretations.

Petrography has been particularly effective in studying millstones (King, 1986; Heldal and Meyer, 2011; Santi et al., 2013), although in this case, analytical programs have tended to focus on specific questions, products, and sources. Well-consolidated, coarse-grained rocks are best suited for grinding stones, but vesicular volcanic rock was particularly sought after as the round voids (vesicles) which developed in the rock from trapped gases create natural cutting edges. The various volcanic sources in the Mediterranean region and the ease with which heavy goods could be transported by sea led to an extensive Roman trade in millstones made from volcanic rock (Williams-Thorpe, 1988).

Ceramic petrography

The most common use of petrography in archaeology is for studying ancient pottery, an application that was pioneered in the 1930s by Anna O. Shepard and Frederick R. Matson (Thompson, 1991). It is most effective with coarse fabrics, in which rock and mineral inclusions can be detected with the naked eye and under the microscope. Fine-grained pottery is often devoid of inclusions and therefore more appropriately studied using methods of chemical analysis (e.g., NAA). In association with compositional studies, ceramic petrography is an effective tool for studying both ancient pottery technology and trade.

In technological studies, compositional and textural information is used to identify potential raw materials and the various ways in which they may have been processed during pottery production. Unlike lithic tool production, in which the stone is shaped but otherwise remains largely unchanged, pottery is a synthetic product of human interaction with clay-based materials. Potters may combine different clays to achieve a preferred paste mixture with which to make a pot. Depending on the clay properties, the size, and the function of a vessel, they may refine their raw materials by removing coarse inclusions (using sieving or levigation) or adding additional nonplastic inclusions (temper), such as sand, to achieve a more workable and effective clay body. The choices made by potters in selecting and working their materials are in many cases defined by their social environment and learning networks, such that differences in technology may be used to identify social boundaries. Petrography is particularly effective in studying these processes because it can determine both the composition and micromorphology of pottery fabrics. It can also compare this information with the results of experimental replication tests (Whitbread, 1995).

Imported pottery can be identified by the presence of nonlocal rocks and minerals in a pottery fabric compared with the geology surrounding the site from which it was excavated. Ceramic fabric refers to the constituent properties of a fired ware, including aspects of its matrix, inclusions, voids, internal structures and organization, and color, but not surface coatings and treatments (Rye, 1981: 145). Although geological literature and maps provide a rapid means of identifying potential source areas, direct comparison with rock, clay, and pottery from the field is also necessary to account for the extent to which potters might have processed their materials. In this respect, direct comparison with pottery fabrics of known origin (control groups), ideally based on material from kiln sites, is especially helpful in distinguishing the products of different potters working in geologically similar areas. Shepard's (1965) study of Rio Grande glaze-paint pottery is a classic example of the basic principles that underlie the application of petrography in studying ancient pottery exchange networks. By comparing the compositions of inclusions in pottery from several archaeological sites along the Rio Grande river, she mapped the distribution of pottery with respect to the occurrence of different geological sources. Shepard was able to propose changes over time in the distribution of locally produced and imported pottery at the various sites.

Perhaps the greatest archaeological impact of ceramic petrography has been in demonstrating the early movement of pottery and particularly the movement of coarse utilitarian pottery. Prior to the application of petrographic studies to pottery, there had been a general assumption among archaeologists that fine decorated pottery was distributed as prestige items but that coarse-grained pottery, generally lacking in decoration or purely utilitarian in function, would have been produced locally.

Numerous studies have shown the fallacy of this assumption (e.g., Quinn, 2009). One of the earliest of these is Peacock's (1969) petrographic analysis of Neolithic "Hembury" ware, distributed across southwestern and southern Britain, which showed that the pottery matched gabbro outcrops on the Lizard peninsula of Cornwall. This finding demonstrated that the pottery was imported rather than locally made when found beyond the extent of the gabbro. Moreover, its distribution roughly coincides with that of Cornish stone axes, possibly resulting from similar exchange networks.

As a technique, ceramic petrography has borrowed heavily from the geological sciences, especially sedimentary petrography, but there have also been a number of attempts to develop and improve its application to archaeological problems. Many properties of pottery fabrics differ from those of sediments owing to the large component of clay matrix and the effects of anthropogenic actions, such as firing of the clay to make pottery. One way to address this issue has been to combine the descriptive methodology of sedimentary petrography with that of soil micromorphology and pottery-specific attributes to provide a more comprehensive system for identifying and describing the micromorphological features encountered in ceramic thin sections (Whitbread, 1995). Ceramic petrography is generally applied as a semiquantitative technique with the relative frequencies of constituents estimated with the aid of comparator charts. Though time-consuming, quantification can produce valuable results, most notably with the technique of point counting in which the area of a thin section is systematically sampled to either count the occurrence of different constituents (Miksa and Heidke, 2001) or to select grains which are measured for size (Stoltman, 1989). Digital image analysis has occasionally been undertaken, but the complex arrangements of polycrystalline grains and voids found in many ceramic fabrics poses a significant challenge to its routine application. Microfossils such as foraminifera and ostracods have been used in aiding the identification of clay sources used for ceramics. In some cases, these fossils are specific to particular chronological units within the sedimentary stratigraphy, and in such situations, the problem posed by widely distributed sedimentary rocks can be reduced by focusing on potential sources from stratigraphic units that lie within the date range represented by the fossil traces (Quinn, 2008).

Anthropogenic materials other than pottery are also suitable for petrographic analysis. This includes the study of mortars, plasters, and cements in which petrographic analysis plays a valuable role in identifying constituents and their interaction during formation of the material (Karkanas, 2007).

Soil micromorphology

Soil micromorphology is a technique for analyzing soils and related sediments that incorporates a significant petrographic component both in hand specimens and thin sections. It is widely used to study natural processes through soil composition and structure, but in archaeological contexts it is especially effective for examining the nature and origin of anthropogenic deposits. An example is the study of "dark earth," apparently homogeneous deposits of dark-colored soil commonly found in urban occupation areas of European medieval sites. Soil micromorphology of such deposits in London, dated by coins to the third to fourth centuries AD, showed that they are composed of decayed materials from timber-framed buildings, mud huts, and occupational refuse mixed through biological activity including rooting plants, burrowing animals, and garden cultivation. They are believed to be a result of intensive occupation by a population that relied heavily on the use of timber and mud building materials (Courty et al., 1989: 261). Soils differ from rocks in many morphological and compositional properties, such as void structures and the presence of humic materials. As a consequence, the technique has developed specialized methods of sampling, thin section preparation, and analysis.

Summary

Petrography is a widely applied and versatile technique for the mineralogical study of rocks and sediments. It complements most alternative methods of materials analysis but is most powerful when undertaken by researchers experienced in the technique and its application to specific archaeological materials.

Bibliography

Clough, T. H. McK., and Woolley, A. R., 1985. Petrography and stone implements. *World Archaeology*, **17**(1), 90–100.

Courty, M.-A., Goldberg, P., and Macphail, R., 1989. *Soils and Micromorphology in Archaeology*. Cambridge: Cambridge University Press.

Dietrich, R. V., and Skinner, B. J., 1979. *Rocks and Rock Minerals*. New York: Wiley.

Goren, Y., and Goldberg, P., 1991. Petrographic thin sections and the development of Neolithic plaster production in northern Israel. *Journal of Field Archaeology*, **18**(1), 131–138.

Heldal, T., and Meyer, G. B., 2011. The rise and fall of the Hyllestad millstone quarry landscape, western Norway. In Williams, D. F., and Peacock, D. P. S. (eds.), *Bread for the People: The Archaeology of Mills and Milling. Proceedings of a Colloquium Held in the British School at Rome 4th–7th November 2009*. Oxford: Archaeopress. BAR International Series, Vol. 2274, pp. 325–339.

Herz, N., and Waelkens, M., 1988. *Classical Marble: Geochemistry, Technology, Trade*. Dordrecht: Kluwer Academic Publishers. NATO ASI Series E, Applied Sciences, Vol. 153.

Hughes, J. J., and Cuthbert, S. J., 2000. The petrography and microstructure of medieval lime mortars from the west of Scotland: implications for the formulation of repair and replacement mortars. *Materials and Structures*, **33**(9), 594–600.

Karkanas, P., 2007. Identification of lime plaster in prehistory using petrographic methods: a review and reconsideration of the data on the basis of experimental and case studies. *Geoarchaeology*, **22**(7), 775–796.

Kile, D. E., 2003. *The Petrographic Microscope: Evolution of a Mineralogical Research Instrument*. Tucson: The Mineralogical Record. Special Publication 1.
King, D., 1986. Petrology, dating and distribution of querns and millstones. The results of research in Bedfordshire, Buckinghamshire, Hertfordshire and Middlesex. *University College London Institute of Archaeology Bulletin*, **23**, 65–126.
Miksa, E. J., and Heidke, J. M., 2001. It all comes out in the wash: actualistic petrofacies modeling of temper provenance, Tonto Basin, Arizona, USA. *Geoarchaeology*, **16**(2), 177–222.
Nesse, W. D., 2004. *Introduction to Optical Mineralogy*, 3rd edn. Oxford: Oxford University Press.
Oleson, J. P., Brandon, C., Cramer, S., Cucitore, R., Gotti, E., and Hohlfelder, R. L., 2004. The ROMACONS project: a contribution to the historical and engineering analysis of hydraulic concrete in Roman maritime structures. *International Journal of Nautical Archaeology*, **33**(2), 199–229.
Olson, V., 2011. *Working with Limestone: The Science, Technology and Art of Medieval Limestone Monuments*. Farnham: Ashgate.
Pavía, S., and Caro, S., 2008. An investigation of Roman mortar technology through the petrographic analysis of archaeological material. *Construction and Building Materials*, **22**, 1807–1811.
Peacock, D. P. S., 1969. Neolithic pottery production in Cornwall. *Antiquity*, **43**(170), 145–149.
Quinn, P. S., 2008. The occurrence and research potential of microfossils in inorganic archaeological materials. *Geoarchaeology*, **23**(2), 275–291.
Quinn, P. S., 2009. *Interpreting Silent Artefacts: Petrographic Approaches to Archaeological Ceramics*. Oxford: Archaeopress.
Rye, O. S., 1981. *Pottery Technology: Principles and Reconstruction*. Washington, DC: Taraxacum. Manuals on Archaeology 4.
Santi, P., Renzulli, A., and Gullo, R., 2013. Archaeometric study of the hopper-rubber and rotary Morgantina-type volcanic millstones of the Greek and Roman periods found in the Aeolian archipelago (southern Italy). *European Journal of Mineralogy*, **25**(1), 39–52.
Shepard, A. O., 1965. Rio Grande glaze-paint pottery: a test of petrographic analysis. In Matson, F. R. (ed.), *Ceramics and Man*. New York: Wenner-Gren Foundation for Anthropological Research. Viking Fund Publications in Anthropology, Vol. 41, pp. 62–87.
St John, D. A., Poole, A. B., and Sims, I., 1998. *Concrete Petrography: A Handbook of Investigative Techniques*. London: Arnold.
Stoltman, J. B., 1989. A quantitative approach to the petrographic analysis of ceramic thin sections. *American Antiquity*, **54**(1), 147–160.
Thompson, R. H., 1991. Shepard, Kidder, and Carnegie. In Lange, F. W., and Bishop, R. L. (eds.), *The Ceramic Legacy of Anna O. Shepard*. Niwot: University Press of Colorado, pp. 11–41.
Vola, G., Gotti, E., Brandon, C., Oleson, J. P., and Hohlfelder, R. L., 2011. Chemical, mineralogical and petrographic characterization of Roman ancient hydraulic concretes cores from Santa Liberata, Italy, and Caesarea Palestinae, Israel. *Periodico di Mineralogia*, **80**(2), 317–338.
Walsh, J. J., 2007. Petrography: distinguishing natural cement from other binders in historical masonry construction using forensic microscopy techniques. *Journal of the American Society for Testing and Materials (ASTM) International*, **4**(1), JAI100674, doi:10.1520/JAI100674.
Whitbread, I. K., 1995. *Greek Transport Amphorae: A Petrological and Archaeological Study*. Athens: British School at Athens. Fitch Laboratory Occasional Paper 4.
Whitbread, I. K., and Mari, A., 2014. Provenance and proximity: a technological analysis of Late and Final Neolithic ceramics from Euripides Cave, Salamis, Greece. *Journal of Archaeological Science*, **41**, 79–88.
Willams-Thorpe, O., 1988. Provenancing and archaeology of Roman millstones from the Mediterranean area. *Journal of Archaeological Science*, **15**(3), 253–305.
Worley, N., 2009. Henry Clifton Sorby (1826–1908) and the development of thin section petrography in Sheffield. In Quinn, P. S. (ed.), *Interpreting Silent Artefacts: Petrographic Approaches to Archaeological Ceramics*. Oxford: Archaeopress, pp. 1–9.

Cross-references

Anthrosols
Ceramics
Electron Probe Microanalyzer
Fourier Transform Infrared Spectroscopy (FTIR)
Geochemical Sourcing
Grain Size Analysis
Inductively Coupled Plasma-Mass Spectrometry (ICP-MS)
Neutron Activation Analysis
Scanning Electron Microscopy (SEM)
Soil Micromorphology
X-ray Diffraction (XRD)
X-ray Fluorescence (XRF) Spectrometry in Geoarchaeology

PIGMENTS

Ian Watts
Athens, Greece

Synonyms

Earth pigments; Hematite; Iron oxides; Ochre; Paints

Definition

Pigments are typically insoluble colorants comprising inorganic compounds; they are distinguished from soluble dyes made from organic compounds. Earth pigments may be any soil, clay, rock, or mineral producing a colored powder with staining power. Informal criteria include the ease with which a material can be powdered, whether the powder is relatively free of gritty impurities, how well it adheres to or stains a surface, and the particular color.

Introduction

By far the most widely reported earth pigments, ethnographically, historically, and archaeologically, are materials enriched in iron oxides (sensu lato), providing colors ranging from pale yellow to dark red, extending to orange and brown (iron oxides providing a black streak, notably magnetite, rarely served as pigments). Yellower forms are commonly called "yellow ochre" (Greek ώχρα – "pale yellow"), while the redder forms are called "red ochre" or "hematite" (generally applied to relatively pure, massive or macrocrystalline expressions of this mineral). The concentration of iron oxides typically results from ubiquitous chemical weathering processes (reductive dissolution followed by migration of Fe^{II} and oxidative reprecipitation as Fe^{III}, with or without hydration). In Paleolithic archaeology, the only other prominent pigment is black manganese (but see Heyes et al., 2016); other forms (e.g., white clay, chalk, graphite, ilmenite) are rare. In the Neolithic and with the formation of early states, a wider range of materials began to be used, improving the color qualities of the existing palette (e.g., mercury and arsenic sulfides [cinnabar, realgar, and orpiment] in the red/orange/yellow range) and expanding the palette to green (primarily "green earths") and blue (primarily copper compounds). This entry focuses on the iron oxide pigments; research on the expanded range of post-Neolithic pigments has largely been restricted to paints and vitreous materials (glass and glazes).

Currently, the earliest secure evidence for pigment use is scraped specularite (a dark, glittery form of hematite), together with a redder form of hematite, from a ~500 ka context at Kathu Pan, Northern Cape, South Africa (Watts et al., 2015). The associated Fauresmith industry is considered transitional between the Acheulean and the Middle Stone Age (MSA), spanning the period from ~600 to ~300 ka. At Kathu Pan and other pigment-associated Fauresmith contexts in the region, pigments are absent in large, underlying Acheulean assemblages, suggesting evidence of absence. At the younger end of this time frame, there is circumstantial evidence for the transport of these pigments over considerable distances (*ibid*.). By ~300 ka, red pigments are also documented in India and possibly in Europe (*ibid*. with refs.), implying a behavioral innovation shared by several hominine lineages. This correlates with early evidence for the establishment of campsites. By ~170 ka, red pigments are ubiquitous to southern African MSA rock shelter occupations (Watts, 2014). This regular and widespread use has been interpreted as the earliest evidence for a symbolic tradition, radiating with the Upper Pleistocene dispersal of Homo sapiens (Watts, 2009). Middle Pleistocene occurrences remain restricted to the pigments themselves, but the African earlier Upper Pleistocene (128–74 ka) provides evidence of paint manufacture (Henshilwood et al., 2011), and a range of objects and contexts (shell beads, bone tools, geometric engravings, and burials [Levant]) are implicated in pigment use (d'Errico and Stringer, 2011).

In Europe, after a few occurrences between ~240 and 200 ka, there follows a prolonged find gap, and occurrences remain rare until ~60 ka. Thereafter, while falling short of the ubiquity seen in southern Africa, Neanderthal use of red ochre and black manganese is widely documented. From ~50 ka, some Neanderthal occurrences are no less suggestive of symbolic culture than earlier African counterparts (Zilhão et al., 2010). The earliest dated rock paintings are contemporaneous in Europe and SE Asia, at ~40 ka (Pike et al., 2012; Aubert et al., 2014). In the European Upper Paleolithic, in addition to rock painting, red ochre is recurrently found in mortuary contexts, and a wide variety of artifacts bear ochre residues. Neolithic usage extends to pottery decoration and wall murals. The Neolithic also sees the first use of cinnabar, a mercury sulfide providing a vermillion pigment (Gajić-Kvaščev et al., 2012). Use of "green earth" as a pigment is largely restricted to literate societies, but it is reported among the stratified hunter-gatherers of the American northwest coast and in Argentine rock painting (Eastaugh et al., 2004, 175). Copper-based synthetic blue pigments first appear in Egypt in the third millennium BC (Riederer, 1997), with a similar development in China around 500 BC (Berke, 2002). Blue glass and glazes, using cobalt compounds, were developed in Mesopotamia and Egypt around 1600 BC (Rehren, 2014; Rehren and Freestone, 2015 with refs.).

Foundational research questions are largely epistemological. Given that typical natural formation processes are ongoing nearly everywhere, when can a pigmentaceous material be considered artifactual (Watts, 2010, 395 with refs.)? To what extent may taphonomic processes have altered the colors of archaeological pigments (Wadley, 2010a)? What warrants an interpretation as pigment rather than for some purpose where color is irrelevant or of secondary importance (Wadley et al., 2009; Watts, 2010)?

Most research concerns procurement, processing, and use. Issues that have received attention are the discrimination of different use-wear traces (Salomon, 2009; Hodgskiss, 2010; Rifkin, 2012; Hodgskiss, 2013); identification of past selection criteria (Watts, 2010); provenancing (e.g., Eiselt et al., 2011; MacDonald et al., 2011); incidental alteration of yellow ochre to red ochre (Wadley, 2010a); deliberate alteration of yellow ochre to red ochre (Salomon et al., 2012); pigment preparation (Wadley, 2010b; Henshilwood et al., 2011); and identification of paint constituents, i.e., pigments and binders/fillers (Rowe, 2001; Jezequel et al., 2011 with refs.; this field overlaps with biochemistry and rock art conservation). Several of these research topics have contributed to a *chaîne opératoire* approach to Paleolithic art (Menu, 2009). Related research has investigated some non-pigment uses (e.g., Audouin and Plisson, 1982; Lombard, 2007; Wadley et al., 2009; Rifkin, 2011; Rifkin et al., 2015).

Evolutionary questions include: What selection pressures motivated this novel behavior, and should it be considered a costly or relatively cheap form of signaling (Power, 2009; Kuhn, 2014; Watts et al., 2015)? Under what conditions might pigment use be considered symbolic (Knight et al., 1995; Kuhn and Stiner, 2007; Pettitt, 2011; Mithen, 2014; Watts, 2015)? How are commonalities and differences in pigment records between hominine lineages to be interpreted (e.g., d'Errico, 2008; Power et al., 2013; Dayet et al., 2014; Watts, 2014)? What can the technology of use tell us about cognitive abilities (Wadley et al., 2009; Henshilwood et al., 2011; Hodgskiss, 2014)?

General characterization

Cornell and Schwertmann (2003) provide an overview of the properties of iron oxides (oxides, hydroxides, and oxide-hydroxides). The principal oxide of interest is hematite (α-Fe_2O_3), which produces a red streak when rubbed across a streak plate to produce a powder. The oxide-hydroxides and hydroxides, with the ligands O^{2-} or OH^- bonded to the Fe^{III+}, comprise a large group, including goethite (α-FeOOH), which produces a yellow streak; lepidocrocite (γ-FeOOH), which produces an orange streak; and ferrihydrite ($Fe_5HO_8.4H_2O$), which produces a red-brown streak. Among these, goethite is probably the most common pigment. Color may be influenced by crystal size and admixtures of iron oxides with or without other chromophores (e.g., manganese). Relatively small amounts of hematite can mask goethite's streak. Elias et al. (2006) evaluate how phase state and accessory minerals influence color.

The hydroxides are transformed to oxides by heating at relatively low temperatures, resulting in dehydration or dehydroxylation, with streaks becoming redder. This may occur incidentally through proximity to hearths or natural fires (Watts, 2010; Wadley, 2010a), or deliberately, with the goal of obtaining a redder pigment (Salomon et al., 2012).

In ochreous admixtures, the most common accessory minerals are phyllosilicates (clay and mica minerals) and framework silicates (quartz), followed by carbonates (e.g., dolomite) and sulfates (e.g., gypsum). The scale at which chemical weathering occurs ranges from cortical surfaces of long exposed nodules, along faults and joints, to the formation of ferruginous lenses and concretions to industrially exploitable ore bodies (frequently involving supergene enrichment, which is a concentration of mineral formation at depth as meteoric water entrains ions lower within an ore body). Almost any sedimentary rock and several igneous rocks (e.g., basalt) may develop ochreous expressions, and there is typically considerable variation within a weathering profile. Iron oxides may also form via metamorphic processes.

Relatively pure hematite – massive or macrocrystalline – is fairly common. Specular hematite (specularite) is characterized by platy crystals and is anomalous in that its principal perceptual salience lies in its glittery appearance rather than color. Depending on platelet size and the fineness of the processed powder, the color may be silvery-black or a dark, low-chroma red.

Iron being a first-row transition metal on the periodic table, small amounts of other transition metals may be substituted within the iron oxide matrix. The patterns most diagnostic of the parent rock, regardless of weathering history, typically concern substitution of transition metals and enrichment of rare earth elements (REEs); elements positively correlated with Fe are the focus of provenance research (Popelka-Filcoff et al., 2008; MacDonald et al., 2011).

The chromophores of "green earths" are clay minerals, most commonly glauconite, which is formed in marine-deposited sandstones and clays, or celadonite, which is a weathering product of basalt (Eastaugh et al., 2004). Malachite (a basic copper carbonate) may occasionally have been used as a green pigment in ancient Egypt, but most green pigments were synthetically produced, using a similar procedure to the production of Egyptian blue (see below) (Lee and Quirke, 2000).

Obtaining a stable blue pigment presented a considerable technological challenge. The most widely available potential chromophore is azurite, a hydrated copper carbonate associated with malachite. Although used as a pigment in classical Greece (Eastaugh et al., 2004, 33), its use in earlier contexts is questionable (Lee and Quirke, 2000, 111). Its major drawback is that the color is unstable. This impermanence is thought to have promoted the development of the first synthetic pigments, Egyptian blue and Chinese blue, alkaline-earth-metal copper silicates, using sand and copper minerals, synthesized with either lime (Egypt) or barium minerals (China) (Berke, 2002). Lapis lazuli (ultramarine) is a rare and complex sodalite mineral (a sulfur-containing aluminum silicate), related to feldspars, where the blue mineral, lazulite, occurs in combination with calcspar and iron pyrite. Although exploited as a precious stone since the Neolithic, its hardness was a factor making it unsuitable as a pigment; it was incorporated into pigments and glazes only in the last two millennia (Eastaugh et al., 2004, 219).

Semiotic uses

The most common ethnographically documented uses of pigments are as body paints and cosmetics, followed by the decoration of a wide range of artifacts (ritual paraphernalia, clothing, tools, and utensils) and rock painting. Much of this usage, particularly among hunter-gatherers, occurs in a wide range of ritual contexts (e.g., Sagona, 1994; Watts, 1999). From an evolutionary perspective, the theoretical focus has to be on ritual display, a form of signaling with well-established characteristics that do not presuppose symbolic culture, but also the mechanism by which collective representations were established and faithfully transmitted in the first place (Watts, 2009 with refs.). In this context, exploitation of perceptual biases to create eye-catching effects are to be expected, with cross-cultural uniformities in the naming of colors (Kay and Maffi, 1999) indicating a preeminent role for dark, saturated reds (Watts, 2010). This is consistent with the finding of preferential use of the reddest and most saturated materials in some MSA assemblages (*ibid.*; Hodgskiss, 2012). To date, the only models engaging with signal evolution theory that generate refutable predictions of early pigment use are the Female Cosmetic Coalitions hypothesis (Knight et al., 1995; Power, 2009; Power et al., 2013) and the "cheap but honest signaling" hypothesis (Kuhn, 2014). Regardless of how late Middle Pleistocene pigments are interpreted, by the early Upper Pleistocene in Africa, and by ~50 ka in Europe, pigment use occurs within and helps define symbolically constructed universes.

Non-semiotic uses

While "pigment" is appropriate as a general term, iron oxide-rich materials have served a variety of other roles (aside from metallurgy), obliging archaeologists to be alert to the many possibilities. Hematite (jeweler's rouge) is used as an abrasive for fine polishing. Ethnographically reported uses include wood preservation (Santhakumaran and Jain, 1983), incorporation into hafting mastics (Dickson, 1981, 164), medicine (Peile, 1979), sun block (de Lange, 1963, 88), and food preservation (Thomson, 1949, 23). Ethnohistorical sources have been cited in support of the use of ochre as an insect repellent (Rifkin 2015), but the present author considers this a contentious interpretation of the literature. Hafting and food preservation currently rest on unique observations, but in the case of hafting, a compelling archaeological case has been made (Lombard, 2007), as also for abrasive uses of hematite (Philibert, 1994; White, 1997; Henshilwood et al., 2001). Such uses are currently documented only from contexts younger than 80 ka. The most widely cited possible utilitarian use is as a tanning agent or hide preservative (e.g., Wadley et al., 2004). This has been questioned because, unlike iron salts, iron oxides are relatively insoluble (Watts, 2009). Experimental research has put the hypothesis on a firmer functional footing (Rifkin, 2011) but also suggests inordinate labor in grinding the large quantities of ochre required (Rifkin, 2012, 191). Social correlates of tanning (prestige goods production) suggest it may not be relevant to early contexts (Hayden, 1990). Most ethnographic accounts indicate that ochre's association with hide working was primarily as a pigment (Dubreuil and Grosman, 2009). Experimental research has demonstrated that ochre powder provides negligible protection against mosquito bites (Rifkin, 2015), but it may provide an effective sun block (Rifkin et al., 2015).

It has recently been proposed, also on experimental grounds, that Neanderthals used manganese dioxide for fire making (Heyes et al.,2016). This might account for the initial appearance of manganese in the glacial conditions around 70 ka (Power et al., 2013).

Analysis

Preliminary steps in a comprehensive assemblage analysis should include a brief inspection of all curated inorganic categories to identify potential pigments, and an evaluation of site geology and geomorphology to identify possible autochthonous, non-artifactual pigmentaceous materials. Watts (2010) provides a framework for physical description, including streak properties and traces of utilization (see also Dayet et al., 2014). Thin section petrography aids fabric characterization and provides insight into overall mineralogy and secondary alteration processes (Iriarte et al., 2009). Field survey of local and regional environments is essential to identifying the variety of potential pigments. For provenancing research, multiple samples from each potential source are needed to establish within-source variation.

Any investigation beyond basic physical characterization requires mineralogical and geochemical analyses. Selection of appropriate techniques will depend on the research questions addressed, the size of available samples, whether nondestructive procedures are requisite, whether quantitative measures are needed, and the sensitivity to rare earths and trace elements required. Paint and residue analyses involve very small samples (milligrams), generally requiring minimally destructive or nondestructive techniques. The most appropriate methods are likely to be spectroscopic. Scanning electron microscopy coupled to energy dispersive X-ray analysis (SEM-EDX) is good for mineralogy and identifying the major oxides and those elements present at the level of a few percent or more. Raman spectroscopy is also suitable for mineralogy and some aspects of crystallography (Edwards, 2005). Transmission electron microscopy (TEM), revealing the size and shape of nanoparticles, has been used to investigate phase transitions (Pomiès et al., 1998; d'Errico et al., 2010). Proton-induced X-ray emissions (PIXE) can provide elemental concentrations in parts per million and have recently been used as a nondestructive method to investigate provenance (Beck et al., 2012). With large assemblages that permit some destructive procedures, traditional X-ray diffraction (XRD) and X-ray fluorescence (XRF) may be sufficient (requiring samples of a gram or more). XRD is primarily used to characterize and identify crystalline materials; amorphous materials aside, XRD can be adapted to become a quantitative method using the Rietveld refinement (Jercher et al., 1998). XRF is suitable for bulk elemental analysis (major oxides); it is appropriate for trace elements only if large samples (5–10 g) can be sacrificed (*ibid.*). If dealing with very small samples and/or requiring full spectrum elemental analysis, inductively coupled plasma mass spectrometry (ICP-MS) or instrumental neutron activation analysis (INAA) is appropriate. Robust provenancing inferences need to demonstrate greater inter- than intra-source variation (the provenance postulate), before characterizing the iron oxide signature (fingerprint) of particular groups. INAA, ICP-MS, and PIXE have also been successfully used (see below). Whatever method is used, bivariate and multivariate statistical techniques are needed to identify groups within the data.

Utilization

As earth pigments have to be reduced to powder, they are typically relatively soft rocks. The principal utilization traces on the raw material are grinding and scraping. A body of observational and experimental work exists distinguishing these different traces (Couraud, 1983; d'Errico and Nowell, 2000; Salomon, 2009; Hodgskiss, 2010; Rifkin, 2012). Scraping tends to be of softer materials, which may provide paler streaks that are less red (Henshilwood et al., 2009). Very soft pigments may have been directly rubbed onto organic surfaces (hides or human skin). Grinding followed by rubbing was identified in a late Mousterian manganese assemblage (Soressi et al., 2008) and in an MSA red ochre assemblage (Hodgskiss, 2013). Rubbed surfaces are particularly hard to identify (Hodgskiss, 2010). Pounding of harder forms, while plausible, would probably require secondary processing of residual coarse particles. To the author's knowledge, it has not been archaeologically identified. In some Middle Pleistocene contexts, flaked pigmentaceous materials have been interpreted as part of the lithic assemblage rather than as pigments (Watts, 2010 with refs.). Rare forms of utilization include notching (*ibid.* with refs) and engraving (Henshilwood et al., 2009; d'Errico et al., 2012).

The survival of use-wear depends on the softness of the material and the depositional environment. White and yellow pigments are particularly likely to be soft and friable. Among red pigments, more hematite-enriched expressions tend to be harder (Watts, 2010; but see Watts et al., 2015). Shelter contexts are more likely to preserve use-wear than open sites; corrosion of surfaces may be particularly severe in sites subject to fluctuating water tables (e.g., spring and pond margins).

Powder production is a general requirement, irrespective of end use as a pigment or for some non-semiotic role. However, pigment use should have more explicit implications for color selection. With large assemblages, past selective criteria can be investigated by comparing the streaks of utilized versus unutilized pieces, controlling for size (Watts, 2010). The intensity of use-wear may also be informative in this respect (Watts, 2009; Hodgskiss, 2013).

History of research

The belated acceptance that painted caves were (Upper) Paleolithic prompted the first chemical analysis of paint constituents (Moissan, 1902) and one of the earliest archaeological reports on ochre processing (Breuil and Cartailhac, 1906). Neanderthal use of manganese and red ochre was established shortly afterwards (Capitan and Peyrony, 1912). The association of pigments with African MSA assemblages was established in the mid-twentieth century (Armstrong, 1931; Tobias, 1949). Mason (1957) regarded the appearance of red ochre in the later stages of the MSA Pietersburg industry as one of the traits indicating directional evolutionary change (see also Watts, 2014). In the early 1970s, MSA specularite mining, which had already stimulated some interesting, if theoretically unconstrained speculation about its symbolic significance (Dart, 1968), was pushed back beyond the limits of ^{14}C dating (Dart and Beaumont, 1971).

Ochre residues on late Upper Paleolithic scrapers began to receive attention in the 1970s, leading to the hide preservation or tanning hypothesis (Keeley, 1980; Audouin and Plisson, 1982), which stimulated a considerable body of work (references in Watts, 2002; Dubreuil and Grosman, 2009; Rifkin, 2011).

The first detailed descriptive account of a pigment assemblage was Couraud and Laming-Emperaire's work at Lascaux (1979). Wreschner (1980) and Schmandt-Besserat (1980) provided literature-based surveys of early use, and Wreschner went on to undertake experimental work addressing heat alteration (1983). Couraud (1983) continued to refine descriptive methods, producing an account of the large Arcy-sur-Cure late Neanderthal assemblages (Couraud, 1991; see also Salomon, 2009). Few other European assemblages have been described in any detail, although recent studies are methodologically exemplary (e.g., Dayet et al., 2014).

In the 1990s, growing acceptance of our recent African origin and the paradox of the apparent lack of evidence for symbolic culture until ~40 ka led to renewed interest in the African MSA pigment record, being the only redundant category of evidence bearing on the issue (Knight et al., 1995; Watts, 1999; Watts, 2002). More detailed descriptive accounts of newly excavated MSA pigment assemblages followed (Watts, 2010, 393 with refs; Hodgskiss, 2012; Dayet et al., 2013; Hodgskiss, 2013).

It was also in the 1990s that archaeometric pigment analyses reached maturity. There are several reviews of the history of these studies (Clottes et al., 1990; Smith et al., 1998; Rowe, 2001; Edwards, 2005; Popelka-Filcoff et al., 2007; Trąbska 2014), each bringing slightly different aspects of the field into focus. After Moissan's pioneering studies at the start of the twentieth century, little archaeometric work had been done until the 1970s. French and Australian analyses in the 1980s focused largely on paints, making extensive use of SEM-EDS and XRD for mineral identifications. In the early 1990s, PIXE began to be applied, being more sensitive for elemental analysis than SEM-EDS (Rowe, 2001). From the mid-1990s, Raman spectroscopy (also for mineralogical identifications) was increasingly used in paint analyses (Edwards, 2005).

Much of the early work on provenancing was Australian. Initial studies worked on improving characterization of source materials using PIXE (David et al., 1993). Some success was achieved by combining Rietveld refinement of XRD spectra (for quantitative phase analysis) with XRF elemental analysis (Jercher et al., 1998). The large sample size requirements of XRF led to the adoption of ICP-MS for elemental study, together with Rietveld XRD (Smith et al., 1998). This study demonstrated changes in procurement behavior in a central Australian site spanning the last 32,000 years, with fingerprinting of two sources. Similar studies were attempted in Israel and the USA (Popelka-Filcoff et al., 2007 with refs.). Notwithstanding the study of Smith and colleagues, most conclusions were tentative.

The real breakthrough occurred in the last decade, with the systematic application of INAA (Popelka-Filcoff et al., 2007; Kiehn et al., 2007; Popelka-Filcoff et al., 2008; Eiselt et al., 2011; MacDonald et al., 2011). This has proved successful in meeting the provenance postulate in a variety of different contexts. Not only can it discriminate fundamentally different pigments, but it opens up prospects for identifying different groups within geologically fairly uniform regions, where the principal differences lie in weathering histories (MacDonald et al., 2011). The proposed underlying mechanism in this instance was clinal geographic differences in rainfall, with concomitant effects on water pH. Most recently, nondestructive PIXE has been used for provenance research (Beck et al., 2012; Mathis et al., 2014).

Bibliography

Armstrong, A. L., 1931. Rhodesian archaeological expedition (1929): excavations in Bambata Cave and researches on prehistoric sites in southern Rhodesia. *Journal of the Royal Anthropological Institute*, **61**, 239–276.

Aubert, M., Brumm, A., Ramli, M., Sutikna, T., Saptomo, E. W., Hakim, B., Morwood, M. J., van den Bergh, G. D., Kinsley, L., and Dosseto, A., 2014. Pleistocene cave art from Sulawesi, Indonesia. *Nature*, **514**(7521), 223–227.

Audouin, F., and Plisson, H., 1982. Les ocres et leurs témoins au Paléolithique en France: enquête et expériences sur leur validité archéologique. *Cahiers du Centre de Recherches Préhistoriques*, **8**, 33–80.

Beck, L., Salomon, H., Lahlil, S., Lebon, M., Odin, G. P., Coquinot, Y., and Pichon, L., 2012. Non-destructive provenance differentiation of prehistoric pigments by external PIXE. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, **273**, 173–177.

Berke, H., 2002. Chemistry in ancient times: the development of blue and purple pigments. *Angewandte Chemie International Edition*, **41**(14), 2483–2487.

Breuil, H., and Cartailhac, É., 1906. L'ocre rouge dans les gisements, sa préparation, ses usages. In Cartailhac, É., and Breuil, H. (eds.), *La caverne d'Altamira à Santillane près Santander (Espagne)*. Monaco: Imprimerie de Monaco, pp. 115–121.

Capitan, L., and Peyrony, D., 1912. Station préhistorique de La Ferrassie, commune de Savignac-du-Bugue (Dordogne). *Revue Anthropologique*, **22**, 29–50, 76–99.

Clottes, J., Menu, M., and Walter, P., 1990. La préparation des peintures magdaléniennes des cavernes ariégeoises. *Bulletin de la Société préhistorique française*, **87**(6), 170–192.

Cornell, R. M., and Schwertmann, U., 2003. *The Iron Oxides: Structure, Properties, Reactions, Occurrences, and Uses*, 2nd edn. Weinheim: Wiley/VCH.

Couraud, C., 1983. Pour une étude méthodologique des colorants préhistoriques. *Bulletin de la Société préhistorique française*, **80**(4), 104–110.

Couraud, C., 1991. Les pigments des grottes d'Arcy-sur-Cure (Yonne). *Gallia préhistoire*, **33**(33), 17–52.

Couraud, C., and Laming-Emperaire, A., 1979. Les colorants. In Leroi-Gourhan, A., and Allain, J. (eds.), *Lascaux inconnu*. Paris: Centre National de la Recherche Scientifique. Supplément à *Gallia préhistoire* 12, pp. 153–170.

d'Errico, F., 2008. *Le rouge et le noir*: implications of early pigment use in Africa, the Near East and Europe for the origin of cultural modernity. *South African Archaeological Society Goodwin Series*, **10**, 168–174.

d'Errico, F., and Nowell, A., 2000. A new look at the Berekhat Ram figurine: implications for the origins of symbolism. *Cambridge Archaeological Journal*, **10**(1), 123–167.

d'Errico, F., and Stringer, C. B., 2011. Evolution, revolution or saltation scenario for the emergence of modern culture. *Philosophical Transactions of the Royal Society B*, **366**(1567), 1060–1069.

d'Errico, F., Salomon, H., Vignaud, C., and Stringer, C., 2010. Pigments from the Middle Palaeolithic levels of Es-Skhul (Mount Carmel, Israel). *Journal of Archaeological Science*, **37**(12), 3099–3110.

d'Errico, F., Moreno, R. G., and Rifkin, R. F., 2012. Technological, elemental and colorimetric analysis of an engraved ochre fragment from the Middle Stone Age levels of Klasies River Cave 1, South Africa. *Journal of Archaeological Science*, **39**(4), 942–952.

Dart, R. A., 1968. The birth of symbology. *African Studies*, **27**(1), 15–27.

Dart, R. A., and Beaumont, P. B., 1971. On a further radiocarbon date for ancient mining in southern Africa. *South African Journal of Science*, **67**(1), 10–11.

David, B., Clayton, E., and Watchman, A., 1993. Initial results of PIXE analysis on Northern Australian ochres. *Australian Archaeology*, **36**, 50–57.

Dayet, L., Texier, P.-J., Daniel, F., and Porraz, G., 2013. Ochre resources from the Middle Stone Age sequence of Diepkloof Rock Shelter, Western Cape, South Africa. *Journal of Archaeological Science*, **40**(9), 3492–3505.

Dayet, L., d'Errico, F., and Garcia-Moreno, R., 2014. Searching for consistencies in Châteperronian pigment use. *Journal of Archaeological Science*, **44**, 180–193.

de Lange, M., 1963. Some traditional cosmetic practices of the Xhosa. *Annals of the Cape Provincial Museums*, **3**, 85–95.

Dickson, F. P., 1981. *Australian Stone Hatchets: A Study in Design and Dynamics*. London: Academic.

Dubreuil, L., and Grosman, L., 2009. Ochre and hide-working at a Natufian burial place. *Antiquity*, **83**(322), 935–954.

Eastaugh, N., Walsh, V., Chaplin, T., and Siddall, R., 2004. *The Pigment Compendium: A Dictionary of Historical Pigments*. Oxford: Elsevier Butterworth-Heinemann.

Edwards, H. G. M., 2005. Case study: prehistoric art. In Edwards, H. G. M., and Chalmers, J. M. (eds.), *Raman Spectroscopy in Archaeology and Art History*. London: Royal Society of Chemistry, pp. 84–96.

Eiselt, B. S., Popelka-Filcoff, R. S., Darling, J. A., and Glascock, M. D., 2011. Hematite sources and archaeological ochres from Hohokam and O'odham sites in central Arizona: an experiment in type identification and characterization. *Journal of Archaeological Science*, **38**(11), 3019–3028.

Elias, M., Chartier, C., Prévot, G., Garay, H., and Vignaud, C., 2006. The colour of ochres explained by their composition. *Materials Science and Engineering B*, **127**(1), 70–80.

Gajić-Kvaščev, M., Stojanović, M. M., Šmit, Ž., Kantarelou, V., Karydas, A. G., Šljivar, D., Milovanović, D., and Andrić, V., 2012. New evidence for the use of cinnabar as a colouring pigment in the Vinča culture. *Journal of Archaeological Science*, **39**(4), 1025–1033.

Hayden, B., 1990. The right rub: hide working in high ranking households. In Gräslund, B., Knutsson, H., Knutsson, K., and Taffinder, J. (eds.), *The Interpretative Possibilities of Microwear Studies: Proceedings of the International Conference on Lithic Use-Wear Analysis, 15th–17th February 1989 in Uppsala, Sweden*. Uppsala: Societas Archaeologica Upsaliensis. AUN 14, pp. 89–102.

Henshilwood, C. S., d'Errico, F., Marean, C. W., Milo, R. G., and Yates, R., 2001. An early bone tool industry from the Middle Stone Age at Blombos Cave, South Africa: implications for the origins of modern human behaviour, symbolism and language. *Journal of Human Evolution*, **41**(6), 631–678.

Henshilwood, C. S., d'Errico, F., and Watts, I., 2009. Engraved ochres from the Middle Stone Age levels at Blombos Cave, South Africa. *Journal of Human Evolution*, **57**(1), 27–47.

Henshilwood, C. S., d'Errico, F., van Niekerk, K. L., Coquinot, Y., Jacobs, Z., Lauritzen, S.-E., Menu, M., and García-Moreno, R.,

2011. A 100,000-year-old ochre-processing workshop at Blombos Cave, South Africa. *Science*, **334**(6053), 219–222.
Heyes, P., Anastasakis, K., de Jong, W., van Hoesel, A., Roebroeks, W., Soressi, M., 2016. Selection and use of manganese dioxide by Neanderthals. *Scientific Reports*, 6, pp. 665–667.
Hodgskiss, T., 2010. Identifying grinding, scoring and rubbing use-wear on experimental ochre pieces. *Journal of Archaeological Science*, **37**(12), 3344–3358.
Hodgskiss, T., 2012. An investigation into the properties of the ochre from Sibudu, KwaZulu-Natal, South Africa. *Southern African Humanities*, **24**(1), 99–120.
Hodgskiss, T., 2013. Ochre use in the Middle Stone Age at Sibudu, South Africa: grinding, rubbing, scoring and engraving. *Journal of African Archaeology*, **11**(1), 75–95.
Hodgskiss, T., 2014. Cognitive requirements for ochre use in the Middle Stone Age at Sibudu, South Africa. *Cambridge Archaeological Journal*, **24**(3), 405–428.
Iriarte, E., Foyo, A., Sánchez, M. A., Tomillo, C., and Setién, C., 2009. The origin and geochemical characterization of red ochres from the Tito Bustillo and Monte Castillo caves (Northern Spain). *Archaeometry*, **51**(2), 231–251.
Jercher, M., Pring, A., Jones, P. G., and Raven, M. D., 1998. Rietveld X-ray diffraction and X- ray fluorescence analysis of Australian Aboriginal ochres. *Archaeometry*, **40**(2), 383–401.
Jezequel, P., Wille, G., Bény, C., Delorme, F., Jean-Prost, V., Cottier, R., Breton, J., Duré, F., and Despriée, J., 2011. Characterization of black and red Magdalenian pigments from Grottes de la Garenne (Vallée moyenne de la Creuse-France): a mineralogical and geochemical approach of the study of prehistorical paintings. *Journal of Archaeological Science*, **38**(6), 1165–1172.
Kay, P., and Maffi, L., 1999. Color appearance and the emergence and evolution of basic color lexicons. *American Anthropologist*, **101**(4), 743–760.
Keeley, L. H., 1980. *Experimental Determination of Stone Tool Uses: A Microwear Analysis*. Chicago: University of Chicago Press.
Kiehn, A. V., Brook, G. A., Glascock, M. D., Dake, J. Z., Robbins, L. H., Campbell, A. C., and Murphy, M. L., 2007. Fingerprinting specular hematite from mines in Botswana, Southern Africa. In Glascock, M. D., Speakman, R. J., and Popelka-Filcoff, R. S. (eds.), *Archaeological Chemistry: Analytical Techniques and Archaeological Interpretation*. Washington, DC: American Chemical Society. ACS Symposium Series 968, pp. 460–479.
Knight, C., Power, C., and Watts, I., 1995. The human symbolic revolution: a Darwinian account. *Cambridge Archaeological Journal*, **5**(1), 75–114.
Kuhn, S. L., 2014. Signaling theory and technologies of communication in the Paleolithic. *Biological Theory*, **9**(1), 42–50.
Kuhn, S. L., and Stiner, M. C., 2007. Body ornamentation as information technology: towards an understanding of the significance of early beads. In Mellars, P., Boyle, K., Bar-Yosef, O., and Stringer, C. (eds.), *Rethinking the Human Revolution: New Behavioural and Biological Perspectives on the Origin and Dispersal of Modern Humans*. Cambridge: McDonald Institute for Archaeological Research. McDonald Institute Monographs, pp. 45–54.
Lee, L., and Quirke, S., 2000. Painting materials. In Nicholson, P. T., and Shaw, I. (eds.), *Ancient Egyptian Materials and Technology*. Cambridge: Cambridge University Press, pp. 104–120.
Lombard, M., 2007. The gripping nature of ochre: the association of ochre with Howiesons Poort adhesives and Later Stone Age mastics from South Africa. *Journal of Human Evolution*, **53**(4), 406–419.
MacDonald, B. L., Hancock, R. G. V., Cannon, A., and Pidruczny, A., 2011. Geochemical characterization of ochre from central coastal British Columbia, Canada. *Journal of Archaeological Science*, **38**(12), 3620–3630.
Mason, R. J., 1957. The Transvaal Middle Stone Age and statistical analysis. *South African Archaeological Bulletin*, **12**(48), 119–137.
Mathis, F., Bodu, P., Dubreuil, O., and Salomon, H., 2014. PIXE identification of the provenance of ferruginous rocks used by Neanderthals. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, **331**, 275–279.
Menu, M., 2009. L'analyse de l'art préhistorique. *L'Anthropologie*, **113**(3), 547–558.
Mithen, S., 2014. The cognition of *Homo neanderthalensis* and *H. sapiens*: does the use of pigment necessarily imply symbolic thought? In Akazawa, T., Ogihara, N., Tanabe, H. C., and Terashima, H. (eds.), *Dynamics of Learning in Neanderthals and Modern Humans, volume 2: Cognitive and Physical Perspectives*. Heidelberg: Springer. Replacement of Neanderthals by Modern Humans Series, pp. 7–16.
Moissan, H., 1902. Sur les matières colorantes des figures de la grotte de Font-de-Gaume. *Compte Rendu de l'Académie des Sciences*, **134**, 1539–1540.
Peile, A. R., 1979. Colours that cure. *Hemisphere*, **23**(4), 214–217.
Pettitt, P., 2011. The living as symbols, the dead as symbols: problematising the scale and pace of hominin symbolic evolution. In Henshilwood, C. S., and d'Errico, F. (eds.), *Homo Symbolicus: The Dawn of Language, Imagination and Spirituality*. Amsterdam: John Benjamins, pp. 141–162.
Philibert, S., 1994. L'ocre et le traitement des peaux: révision d'une conception traditionelle par l'analyse fonctionelle des grattoirs ocrés de la Balma Margineda (Andorre). *L'Anthropologie*, **98** (2–3), 447–453.
Pike, A. W. G., Hoffmann, D. L., García-Diez, M., Pettitt, P. B., Alcolea, J., De Balbin, R., González-Sainz, C., de las Heras, C., Lasheras, J. A., Montes, R., and Zilhão, J., 2012. U-series dating of Paleolithic art in 11 caves in Spain. *Science*, **336**(6087), 1409–1413.
Pomiès, M. P., Morin, G., and Vignaud, C., 1998. XRD study of the goethite-hematite transformation: application to the identification of heated prehistoric pigments. *European Journal of Solid State and Inorganic Chemistry*, **35**(1), 9–25.
Popelka-Filcoff, R. S., Roberston, J. D., Glascock, M. D., and Descantes, C., 2007. Trace element characterization of ochre from geological sources. *Journal of Radioanalytical and Nuclear Chemistry*, **272**(1), 17–27.
Popelka-Filcoff, R. S., Miksa, E. J., Robertson, J. D., and Glascock, M. D., 2008. Elemental analysis and characterization of ochre sources from southern Arizona. *Journal of Archaeological Science*, **35**(3), 752–762.
Power, C., 2009. Sexual selection models for the emergence of symbolic communication: why they should be reversed. In Botha, R., and Knight, C. (eds.), *The Cradle of Language*. Oxford: Oxford University Press, pp. 257–280.
Power, C., Sommer, V., and Watts, I., 2013. The seasonality thermostat: female reproductive synchrony and male behavior in monkeys, Neanderthals, and modern humans. *PaleoAnthropology*, **2013**, 33–60.
Rehren, T., 2014. Glass production and consumption between Egypt, Mesopotamia and the Aegean. In Pfälzner, P., Niehr, H., Pernicka, E., Lange, S., and Köster, T. (eds.), *Contextualising Grave Inventories in the Ancient Near East*. Harrassowitz: Wiesbaden. Qatna Studien Supplementa 3, pp. 217–224.
Rehren, T., and Freestone, I., 2015. Ancient glass: from kaleidoscope to crystal ball. *Journal of Archaeological Science*, **56**, 233–241

Riederer, J., 1997. Egyptian blue. In FitzHugh, E. W. (ed.), *Artists' Pigments: A Handbook of their History and Characteristics*. Washington, DC: National Gallery of Art, Vol. 3, pp. 23–45.

Rifkin, R. F., 2011. Assessing the efficacy of red ochre as a prehistoric hide tanning ingredient. *Journal of African Archaeology*, **9**(2), 131–158.

Rifkin, R. F., 2012. Processing ochre in the Middle Stone Age: testing the inference of prehistoric behaviours from actualistically derived experimental data. *Journal of Anthropological Archaeology*, **31**(2), 174–195.

Rifkin, R. F., 2015. Ethnographic and experimental perspectives on the efficacy of ochre as a mosquito repellent. *South African Archaeological Bulletin*, **70**(201), 64-75.

Rifkin, R., Dayet, L., Queffelec, A., Summers, B., Latagan, M., d'Errico, F., 2015. Evaluating the photoprotective effects of ochre on human skin by In Vivo SPF assessment: Implications for human evolution, adaptation and dispersal. PLoS ONE 10 (9): e0136090. In Vivo, **10**(9).

Rowe, M. W., 2001. Physical and chemical analysis. In Whitley, D. S. (ed.), *Handbook of Rock Art Research*. Walnut Creek: Altamira Press, pp. 190–220.

Sagona, A. G. (ed.), 1994. *Bruising the Red Earth: Ochre Mining and Ritual in Aboriginal Tasmania*. Melbourne: Melbourne University Press.

Salomon, H., 2009. *Les matières colorants au début du Palé olithique supérieur: sources, transformations et fonctions*. PhD dissertation, University of Bordeaux 1.

Salomon, H., Vignaud, C., Coquinot, Y., Beck, L., Stringer, C., Strivay, D., and d'Errico, F., 2012. Selection and heating of colouring materials in the Mousterian level of Es-Skhul (c. 100 000 years BP, Mount Carmel, Israel). *Archaemetry*, **54**(4), 698–722.

Santhakumaran, L. N., and Jain, J. C., 1983. Deterioration of fishing craft in India by marine wood-borers. *Journal of the Indian Academy of Wood Science*, **14**, 35–52.

Schmandt-Besserat, D., 1980. Ocher in prehistory: 300,000 years of the use of iron ores as pigments. In Wertime, T. A., and Muhly, J. D. (eds.), *The Coming of the Age of Iron*. New Haven/London: Yale University Press, pp. 127–150.

Smith, M. A., Fankhauser, B., and Jercher, M., 1998. The changing provenance of red ochre at Puritjarra rock shelter, central Australia: late Pleistocene to present. *Proceedings of the Prehistoric Society*, **64**, 275–292.

Soressi, M., Rendu, W., Texier, J.-P., Claud, E., Daulny, L., d'Errico, F., Laroulandie, V., Maureille, B., Niclot, M., Schwortz, M., and Tillier, A.-M., 2008. Pech-de-l'Azé I - (Dordogne, France): nouveau regard sur un gisement moustérien de tradition acheuléenne connu depuis le 19ème siècle. In Jaubert, J., Bordes, J.-G., and Ortega, I. (eds.), *Les sociétés du Paléolithique dans un grand Sud-Ouest de la France: nouveaux gisements, nouvelles méthodes, nouveaux resultants*. Paris: Société préhistorique française. Mémoire de la Société préhistorique française 47, pp. 95–132.

Thomson, D. F., 1949. *Economic Structure and the Ceremonial Exchange Cycle in Arnhem Land*. Melbourne: Macmillan.

Tobias, P. V., 1949. The excavation of Mwulu's Cave, Potgietersrust District. *South African Archaeological Bulletin*, **4**(13), 2–13.

Trąbska, J., 2014. Provenancing of red ferruginous artefacts and raw materials in Palaeolithic societies. In Biró, K. T., Markó, A., and Bajnok, K. P. (eds.), *Aeolian Scripts: New Ideas on the Lithic World: Studies in Honour of Viola T. Dobosi*. Budapest: Magyar Nemzeti Múzeum. Inventaria Praehistorica Hungariae 13, pp. 245–254. Also http://mek.oszk.hu/09200/09253/pdf/trabska.pdf.

Wadley, L., 2010a. A taphonomic study of ochre demonstrates post-depositional color transformation. *Journal of Taphonomy*, **8** (2–3), 267–278.

Wadley, L., 2010b. Cemented ash as a receptacle or work surface for ochre powder production at Sibudu, South Africa, 58,000 years ago. *Journal of Archaeological Science*, **37**(10), 2397–2406.

Wadley, L., Williamson, B., and Lombard, M., 2004. Ochre in hafting in Middle Stone Age southern Africa: a practical role. *Antiquity*, **78**(301), 661–675.

Wadley, L., Hodgskiss, T., and Grant, M., 2009. Implications for complex cognition from the hafting of tools with compound adhesives in the Middle Stone Age, South Africa. *Proceedings of the National Academy of Sciences*, **106**(24), 9590–9594.

Watts, I., 1999. The origin of symbolic culture. In Dunbar, R. I. M., Knight, C., and Power, C. (eds.), *The Evolution of Culture: An Interdisciplinary View*. Edinburgh: Edinburgh University Press, pp. 113–146.

Watts, I., 2002. Ochre in the Middle Stone Age of southern Africa: ritualised display or hide preservative? *South African Archaeological Bulletin*, **57**(175), 1–14.

Watts, I., 2009. Red ochre, body painting and language: interpreting the Blombos ochre. In Botha, R., and Knight, C. (eds.), *The Cradle of Language*. Oxford: Oxford University Press, pp. 62–92.

Watts, I., 2010. The pigments from Pinnacle Point Cave 13B, Western Cape, South Africa. *Journal of Human Evolution*, **59**(3–4), 392–411.

Watts, I., 2014. The red thread: pigment use and the evolution of collective ritual. In Dor, D., Knight, C., and Lewis, J. (eds.), *The Social Origins of Language*. Oxford: Oxford University Press, pp. 208–227.

Watts, I., 2015. Early color symbolism. In Elliot, A. J., and Fairchild, M. D. and Franklin, A. (eds.), *Handbook of Color Psychology*. Cambridge: Cambridge University Press, pp. 319–339.

Watts, I., Chazan, M., and Wilkins, J., 2015. Early evidence for brilliant ritualized display: specularite use in the Northern Cape, South Africa, between ~500 ka and ~300 ka. *Current Anthropology*.

White, R., 1997. Substantial acts: from materials to meaning in Upper Paleolithic representation. In Conkey, M. W., Soffer, O., Stratmann, D., and Jablonski, N. G. (eds.), *Beyond Art: Pleistocene Image and Symbol*. San Francisco: California Academy of Sciences. Memoirs of the California Academy of Sciences, Vol. 23, pp. 93–122.

Wreschner, E. E., 1980. Red ochre and human evolution: a case for discussion. *Current Anthropology*, **21**(5), 631–644.

Wreschner, E. E., 1983. *Studies in Prehistoric Ochre Technology*. PhD thesis, Hebrew University.

Zilhão, J., Angelucci, D. E., Badal-García, E., d'Errico, F., Daniel, F., Dayet, L., Douka, K., Higham, T. F. G., Martínez-Sánchez, M. J., Montes-Bernárdez, R., Murcia-Mascarós, S., Pérez-Sirvant, C., Roldán-García, C., Vanhaeren, M., Villaverde, V., Wood, R., and Zapata, J., 2010. Symbolic use of marine shells and mineral pigments by Iberian Neandertals. *Proceedings of the National Academy of Sciences*, **107**(3), 1023–1028.

Cross-references

Blombos Cave
Chemical Alteration
Field Survey
Geochemical Sourcing
Inductively Coupled Plasma-Mass Spectrometry (ICP-MS)
Neutron Activation Analysis
Raman
X-ray Diffraction (XRD)
X-ray Fluorescence (XRF) Spectrometry in Geoarchaeology

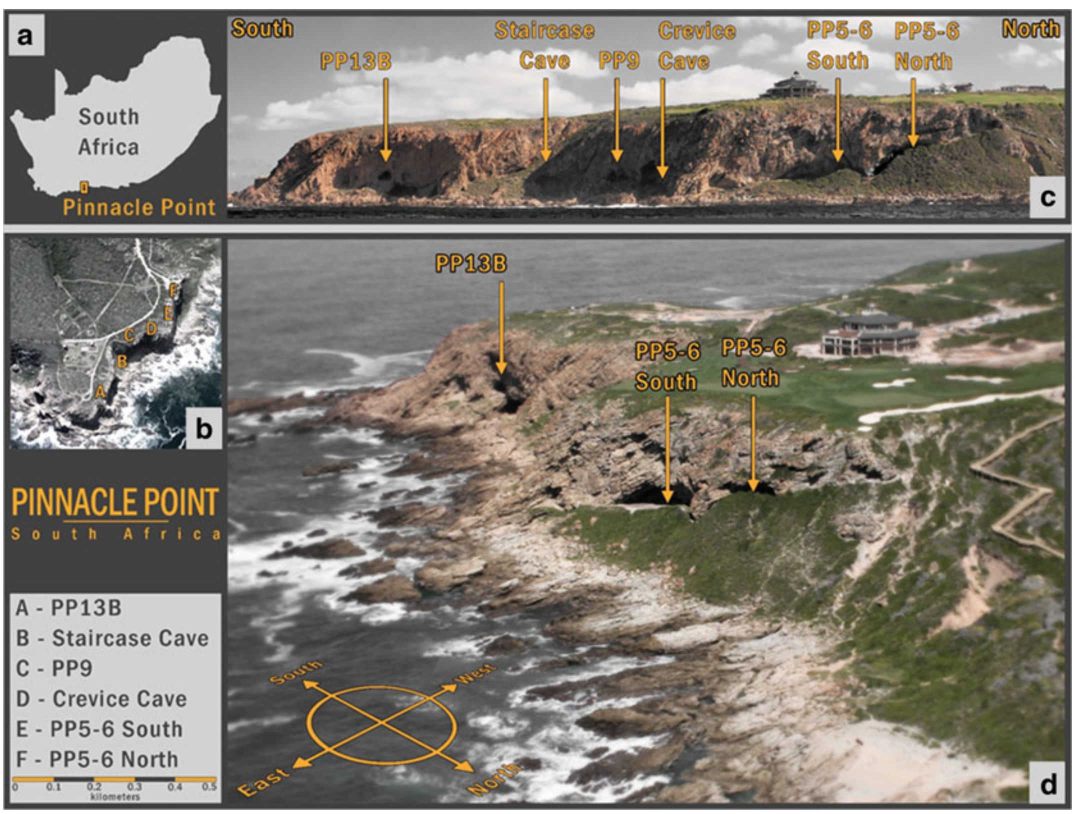
PINNACLE POINT

Curtis W. Marean
Institute of Human Origins, School of Human Evolution and Social Change, Arizona State University, Tempe, AZ, USA
Centre for Coastal Palaeoscience, Nelson Mandela Metropolitan University, Port Elizabeth, Eastern Cape, South Africa

Pinnacle Point is a rocky headland on the south coast of South Africa (Figure 1) on the Indian Ocean that preserves an abundance of caves and rock-shelters. These sites have gained scientific renown from the rich, well-preserved archaeological records dating to the origins of modern humans and also from the widely multidisciplinary approach of the scientific team working there (the South African Coast Paleoclimate, Paleoenvironment, Paleoecology, Paleoanthropology Project, or SACP4). Research began in 1999 and continues today. The regional environmental context is notable for being near the east-west center of the highly diverse Greater Cape Floristic Region (GCFR), which has the world's greatest diversity of geophytic plants, as well as being on a coast with one of the world's richest intertidal zones. These resources are thought to have been resistant to the aridification brought on by glacial phases that affected most of Africa and depressed its resource productivity, therefore making the south coast of the GCFR a likely glacial refugium zone for the progenitor population of modern humans (Marean, 2010, 2011).

The caves and rock-shelters occur in quartzite of the Table Mountain Sandstone formation, which in much of this area is overlain by calcrete formations (Figure 2). All of the caves and rock-shelters were eroded by ancient high sea levels, and recent dating by the SACP4 team using uranium–lead on speleothem and thermal transfer optically stimulated luminescence (TT-OSL) on sands provides concordant evidence that the caves were in place by ~1.1 Ma (Jacobs et al., 2011; Pickering et al., 2013). Our studies show that the peak of the Marine Isotope Stage 11 high sea stand at ~400 ka in this area was at +13 msl (Roberts et al., 2012), which would have washed out most of the >400 ka sediments from the caves, though some of the sites have portions that are sufficiently high to preserve older sediments.

Extending beyond the south coast is a wide, gradually sloping continental shelf called the Agulhas Bank. This



Pinnacle Point, Figure 1 The location of Pinnacle Point and the major sites mentioned in the text (Graphic by Erich Fisher).

Pinnacle Point, Figure 2 The PP13 cave complex; PP13B is the large cave with the constructed stairway leading up to it. The rock into which the caves extend is quartzite of the Table Mountain Sandstone formation; the capping calcrete is too thin at the cliff edge to be apparent.

shelf would have been variably exposed during lower sea levels of the Pleistocene (van Andel, 1989), exposing an entirely novel ecosystem for this area called the Paleo-Agulhas Plain (Marean et al., 2014). SACP4 developed a 3D model of this offshore platform that is integrated with the global sea-level curve, allowing the continuous temporal projection of the coastline distance and configuration over the last 420,000 years (Fisher et al., 2010). A geophysical study of the offshore sediments is enriching our knowledge of that now submerged ancient paleoscape and its ecology (Cawthra et al., 2015). It is hypothesized that there was an east-west migration ecosystem of large ungulates that wintered in the west and summered in the east, taking advantage of the seasonally bipolar rainfall systems (Marean, 2010).

As sea levels rose and fell with glacial retreats and advances, sources of sand were exposed that regularly formed dunes in the region. These dunes sometimes covered the coastal cliffs and closed the caves and rockshelters partially or completely. During these phases of closure when people were excluded, speleothems formed in the caves. SACP4 researchers have identified a series of dune pulses at ~120 ka, 90 ka, and 70 ka (Jacobs, 2010) and have studied the speleothems to develop long and continuous sequences of climate and environmental change for this region. These studies suggest that during MIS 4 (~74–60 ka), the area received greater amounts of rain from the east, which falls in the summer, resulting in a westward expansion of the more classically tropical vegetation of the east coast (Bar-Matthews et al., 2010). Ongoing studies of the speleothems have now pushed this record back to 500 ka and beyond (Braun, 2014).

The timespan of modern human origins in Africa is referred to as the Middle Stone Age (MSA), a technological phase recognized by the way stone artifacts were made. SACP4 has developed at Pinnacle Point the longest and highest resolution record of MSA occupation for Africa. So far, the earliest numerically dated occupations at Pinnacle Point begin at ~160 ka during MIS 6 (~190–125 ka), and this is the only coastal occupation numerically dated to MIS 6 yet discovered in South Africa. Our coastline model shows that at this time, the coast had approached the site to within 7–5 km and people exploited shellfish from the upper portions of the intertidal zone, scavenged seals (Thompson, 2010), and worked ochres that were intentionally selected for their redness. This is the earliest evidence for these behaviors worldwide (Marean et al., 2007; Jerardino and Marean, 2010; Watts, 2010). At this time, people were using heat treatment of stone for artifact production, which is the earliest record yet for this technology, though its use does not become intensive until much later in MIS

Pinnacle Point, Figure 3 The location of PP5-6. The vegetated slope indicated by the *red arrow* is a dune that drapes the outer eroded section of the site.

4 (Brown et al., 2009). The site was alternately lightly occupied or abandoned throughout the rest of MIS 6, and then occupation intensity rises abruptly as the coastline returned to the proximity of the site at the beginning of MIS 5 around ~110 ka. During the rest of MIS 5, occupation intensities were high to moderate as the coast remained within reach of the cave occupants, and then at 90 ka, the cave was abruptly closed to human occupation when a dune sealed it (Karkanas and Goldberg, 2010; Marean et al., 2010).

PP5-6 (Figure 3) is currently still under excavation and analysis, but an intensive OSL dating study complemented by a detailed analysis of micro-facies using micromorphology has provided a high-resolution sequence through the ~14 m tall vertical sediment stack (Karkanas et al., 2015). This sequence dates from ~90 to 50 ka, picking up at the time when PP13B was sealed. The sequence documents a turnover from roof spall-dominated sedimentation to aeolian-dominated sedimentation near the MIS 5–MIS 4 boundary. Occupation intensities actually rose with the glacial MIS 4 (Karkanas et al., 2015), while at the same time there was a shift to the world's earliest known microlithic technology (Brown et al., 2012). Mollusk exploitation continued through the sequence, and there is clear documentation of shell midden production and formal coastal adaptations (Marean, 2014). In the near future, the PP5-6 sequence will be published in detail, and PP13B and PP5-6 together will deliver a record of early human use of coastal environments unrivaled in detail and completeness.

Bibliography

Bar-Matthews, M., Marean, C. W., Jacobs, Z., Karkanas, P., Fisher, E. C., Herries, A. I. R., Brown, K. S., Williams, H. M., Bernatchez, J., Ayalon, A., and Nilssen, P. J., 2010. A high resolution and continuous isotopic speleothem record of paleoclimate and paleoenvironment from 90 to 53 ka from Pinnacle Point on the south coast of South Africa. *Quaternary Science Reviews*, **29**(17–18), 2131–2145.

Braun, K., 2014. *Influence of the Agulhas Current on the Terrestrial Climate of South Africa as Derived from Speleothems*. PhD thesis, Jerusalem: Institute of Earth Sciences, Hebrew University.

Brown, K. S., Marean, C. W., Herries, A. I. R., Jacobs, Z., Tribolo, C., Braun, D., Roberts, D. L., Meyer, M. C., and Bernatchez, J., 2009. Fire as an engineering tool of early modern humans. *Science*, **325**(5942), 859–862.

Brown, K. S., Marean, C. W., Jacobs, Z., Schoville, B. J., Oestmo, S., Fisher, E. C., Bernatchez, J., Karkanas, P., and Matthews, T., 2012. An early and enduring advanced technology originating 71,000 years ago in South Africa. *Nature*, **491**(7425), 590–593.

Cawthra, H. C., Compton, J. S., Fisher, E. C., and Marean, C. W., 2015. Drowned shorelines and submerged terrestrial landscape features off the South African south coast. In Harff, J., Bailey, G., and Lüth, F. (eds.), *Geology and Archaeology: Submerged Landscapes of the Continental Shelf*. Special Publication of the Geological Society of London. doi:10.1144/SP411.11.

Fisher, E. C., Bar-Matthews, M., Jerardino, A., and Marean, C. W., 2010. Middle and Late Pleistocene paleoscape modeling along the southern coast of South Africa. *Quaternary Science Reviews*, **29**(11–12), 1382–1398.

Jacobs, Z., 2010. An OSL chronology for the sedimentary deposits from Pinnacle Point Cave 13B – a punctuated presence. *Journal of Human Evolution*, **59**(3–4), 289–305.

Jacobs, Z., Roberts, R. G., Lachlan, T. J., Karkanas, P., Marean, C. W., and Roberts, D. L., 2011. Development of the SAR TT-OSL procedure for dating Middle Pleistocene dune and shallow marine deposits along the southern Cape coast of South Africa. *Quaternary Geochronology*, **6**(5), 491–513.

Jerardino, A., and Marean, C. W., 2010. Shellfish gathering, marine paleoecology and modern human behavior: perspectives from cave PP13B, pinnacle point, South Africa. *Journal of Human Evolution*, **59**(3–4), 412–424.

Karkanas, P., and Goldberg, P., 2010. Site formation processes at Pinnacle Point Cave 13B (Mossel Bay, Western Cape Province, South Africa): resolving stratigraphic and depositional complexities with micromorphology. *Journal of Human Evolution*, **59** (3–4), 256–273.

Karkanas, P., Brown, K. S., Fisher, E. C., Jacobs, Z., and Marean, C. W., 2015. Interpreting human behavior from depositional rates and combustion features through the study of sedimentary microfacies at site Pinnacle Point 5–6, South Africa. *Journal of Human Evolution*, **85**, 1–21.

Marean, C. W., 2010. Pinnacle Point Cave 13B (Western Cape Province, South Africa) in context: the Cape Floral kingdom, shellfish, and modern human origins. *Journal of Human Evolution*, **59**(3–4), 425–443.

Marean, C. W., 2011. Coastal South Africa and the co-evolution of the modern human lineage and coastal adaptations. In Bicho, N. F., Haws, J. A., and Davis, L. G. (eds.), *Trekking the Shore: Changing Coastlines and the Antiquity of Coastal Settlement*. New York: Springer, pp. 421–440.

Marean, C. W., 2014. The origins and significance of coastal resource use in Africa and Western Eurasia. *Journal of Human Evolution*, **77**, 17–40.

Marean, C. W., Bar-Matthews, M., Bernatchez, J., Fisher, E., Goldberg, P., Herries, A. I. R., Jacobs, Z., Jerardino, A., Karkanas, P., Minichillo, T., Nilssen, P. J., Thompson, E., Watts, I., and Williams, H. W., 2007. Early human use of marine resources and pigment in South Africa during the Middle Pleistocene. *Nature*, **449**(7164), 905–908.

Marean, C. W., Bar-Matthews, M., Fisher, E., Goldberg, P., Herries, A., Karkanas, P., Nilssen, P. J., and Thompson, E., 2010. The stratigraphy of the Middle Stone Age sediments at Pinnacle Point Cave 13B (Mossel Bay, Western Cape Province, South Africa). *Journal of Human Evolution*, **59** (3–4), 234–255.

Marean, C. W., Cawthra, H. C., Cowling, R. M., Esler, K. J., Fisher, E., Milewski, A., Potts, A. J., Singels, E., and De Vynck, J., 2014. Stone Age people in a changing South African Greater Cape Floristic Region. In Allsopp, N., Colville, J. F., and Verboom, G. A. (eds.), *Fynbos: Ecology, Evolution, and Conservation of a Megadiverse Region*. Oxford: Oxford University Press, pp. 164–199.

Pickering, R., Jacobs, Z., Herries, A. I. R., Karkanas, P., Bar-Matthews, M., Woodhead, J. D., Kappen, P., Fisher, E., and Marean, C. W., 2013. Paleoanthropologically significant South African sea caves dated to 1.1–1.0 million years using a combination of U–Pb, TT-OSL and palaeomagnetism. *Quaternary Science Reviews*, **65**, 39–52.

Roberts, D. L., Karkanas, P., Jacobs, Z., Marean, C. W., and Roberts, R. G., 2012. Melting ice sheets 400,000 yr ago raised sea level by 13 m: past analogue for future trends. *Earth and Planetary Science Letters*, **357–358**, 226–237.

Thompson, J. C., 2010. Taphonomic analysis of the Middle Stone Age faunal assemblage from Pinnacle Point Cave 13B, Western Cape, South Africa. *Journal of Human Evolution*, **59**(3–4), 321–339.

Van Andel, T. H., 1989. Late Pleistocene sea levels and the human exploitation of the shore and shelf of southern South Africa. *Journal of Field Archaeology*, **16**(2), 133–155.

Watts, I., 2010. The pigments from Pinnacle Point Cave 13B, Western Cape, South Africa. *Journal of Human Evolution*, **59**(3–4), 392–411.

Cross-references

Data Visualization
Optically Stimulated Luminescence (OSL) Dating
Pigments
Speleothems
U-Series Dating

POMPEII AND HERCULANEUM

Maria Rosaria Senatore
Dipartimento di Scienze e Tecnologie, Università degli Studi del Sannio, Benevento, Italy

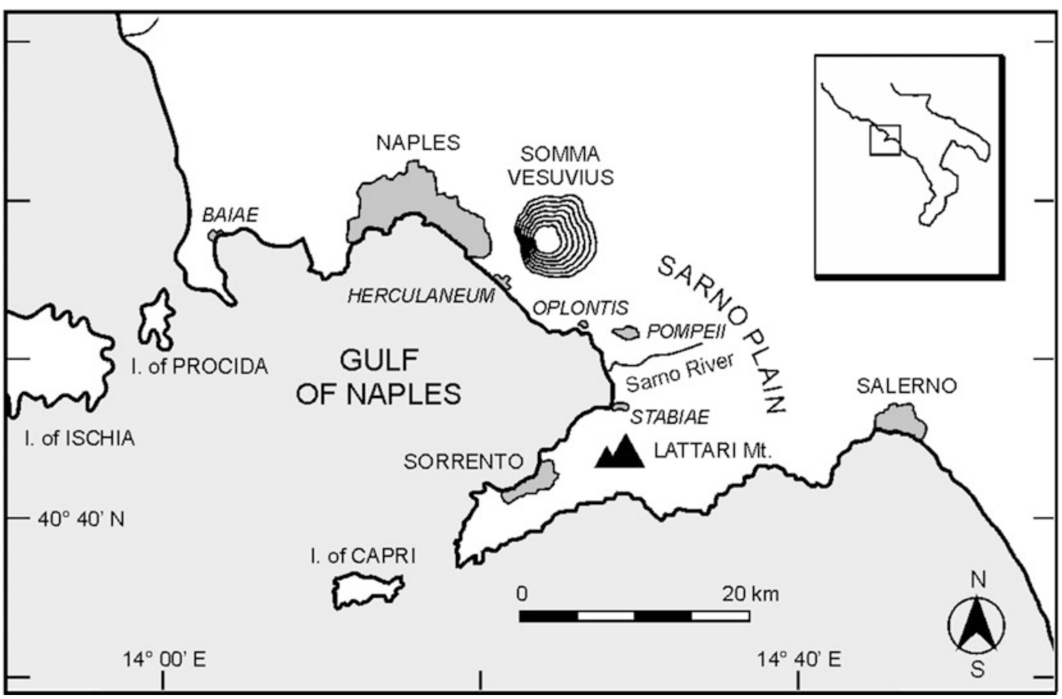
The famous AD 79 volcanic eruption of Vesuvius buried the cities of Pompeii (Figure 1), Herculaneum, and Stabiae, as well as many villas located along the coast south of Naples in southern Italy (Figure 2). The event was described by Pliny the Younger in two letters that were sent to inform Tacitus that the eruption had killed his uncle, Pliny the Elder. It began with a phreatomagmatic explosion followed in the early afternoon of August 24 by a very intense explosive phase leading to the formation of an eruptive column 32 km high, elongated toward the southeast by stratospheric winds. Pliny the Younger compared the shape of the volcanic cloud to a Mediterranean pine. The pyroclastic products related to this phase consisted of pumice fall deposits that mantled the topography to the southeast as a uniform layer with decreasing thickness downwind from Vesuvius. The next day, August 25, volcanic activity changed as a result of collapse of the eruptive column within the volcano. Dense clouds formed as the plume descended, sending gases and pyroclastic products (pyroclastic flows and

Pompeii and Herculaneum, Figure 1 Pompeii, the Arch of Caligula and the view of Vesuvius through it.

surges) rapidly down the slopes at speeds greater than 100 km/h and a temperature of about 400 °C. The first two surges struck Herculaneum on the southwestern side of the volcano, killing all the residents still in the city. Subsequent surges and pyroclastic flows reached as far as Pompeii and the plain of the Sarno River up to Stabiae, all lying to the southeast, destroying everything and killing the inhabitants who, after fleeing during the initial, Plinian (explosive) phase of the eruption, had returned to retrieve their belongings. The products of these pyroclastic flows and surges completely buried Herculaneum and partially covered Pompeii and Stabiae. Volcanic activity continued for some weeks with phreatomagmatic explosions (Sigurdsson et al., 1985; Rolandi et al., 1998; Guest et al., 2003).

The best exposures of these successive volcanic deposits are seen in the excavations of the Herculaneum waterfront and outside the walls of Pompeii at its Herculaneum Gate (northwest, Figure 3) and in the necropolis near Nocera Gate (southeast).

The AD 79 pyroclastic deposits represent a tephra layer that has completely preserved the natural environments existing prior to the eruption; it also serves as a stratigraphic marker useful for paleoenvironmental reconstructions. Stratigraphic and sedimentological research carried out on sediment cores from 25 boreholes collected over a wide area around Pompeii, as well as the reinterpretation of about 400 stratigraphic records from

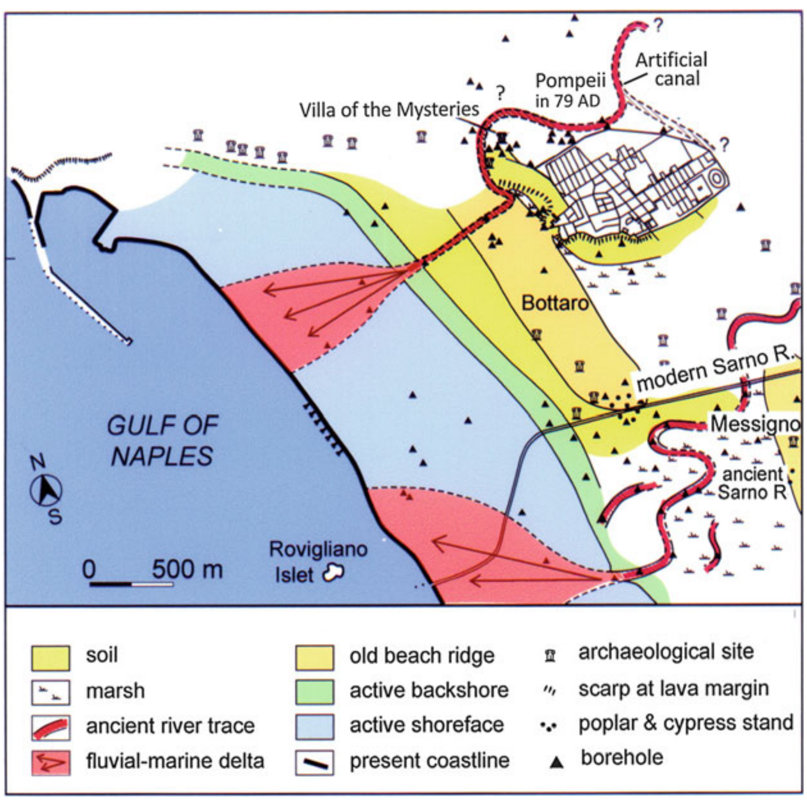


Pompeii and Herculaneum, Figure 2 Location of Pompeii, Herculaneum, Stabiae, and the Sarno River in southern Italy's Campania region. Mt Vesuvius is a younger volcanic cone that has risen within the caldera of a larger and older volcano, Mt Somma. They are often considered together as Somma-Vesuvius.

Pompeii and Herculaneum, Figure 3 AD 79 pyroclastic deposits outside the northwestern walls of Pompeii.

old boreholes, has permitted the reconstruction of the natural Pompeian landscape prior to the eruption (Pescatore et al., 1999, 2001; Pescatore and Senatore, 2005; Ciarallo et al., 2007; Senatore et al., 2010, 2014). Findings suggest that the ancient shoreline of the first century AD was located about 1 km landward of the modern one (Figure 4). Inland and running parallel to the coast, there were two elongated ridges consisting of beach sand deposits, dated by ^{14}C to the Bottaro (3600 BP) and Messigno (5600 BP) stages, marking progressive shoreline progradation over the course of the late Holocene. These coastal ridges were cut by alluvial sand and gravel and by marsh mud deposits related to the ancient Sarno River, which flowed through them and into the sea, forming a well developed delta just southeast of the Rovigliano Islet.

The city of Pompeii was built on an ancient Vesuvian lava flow or, as interpreted by Cinque and Irollo (2004), on remains of a separate volcano and stood in relief with respect to the surrounding plain (Figure 4). To the north of the city, there was an artificial canal. It flowed close to the city (Ciarallo et al. 2003; Senatore et al., 2004, 2014) and probably represented Pompeii's water supply until construction of a Roman aqueduct in the first century BC. The canal flowed toward the Villa of the Mysteries (northwest of the town), then turned toward the south, collected the city's wastewater, and finally turned westward, reaching the coast where it formed a small delta.



Pompeii and Herculaneum, Figure 4 Reconstruction of the territory of the Sarno plain around Pompeii prior to the AD 79 Vesuvius eruption (Modified from Senatore et al., 2004).

Bibliography

Ciarallo, A., Pescatore, T., and Senatore, M. R., 2003. Su di un antico corso d'acqua a nord di Pompei. Dati preliminari. *Rivista di Studi Pompeiani*, **14**, 273–283.

Ciarallo, A., Pescatore, T., and Senatore, M. R., 2007. Le Saline d'Ercole. Primi risultati delle ricerche in corso per la localizzazione del sito. *Rivista di Studi Pompeiani*, **18**, 203–204.

Cinque, A., and Irollo, G., 2004. Il "Vulcano di Pompei": nuovi dati geomorfologici e stratigrafici. *Il Quaternario Italian Journal of Quaternary Sciences*, **17**(1), 101–116.

Guest, J. E., Cole, P. D., Duncan, A. M., and Chester, D. K., 2003. *Volcanoes of Southern Italy, Chapter 2: Vesuvius*. London: The Geological Society of London, pp. 25–62.

Pescatore, T., and Senatore, M. R., 2005. Il paesaggio naturale intorno Pompei prima dell'eruzione vesuviana del 79 d.C.: aspetti geologici e sedimentologici. In Pescatore, T., and Senatore, M. R. (eds.), *Congresso Scienze e Archeologia: Giornate di Studio. Le Scienze Ambientali. Pompei 23 Ottobre 2003*. Pompei: Fotolito Sicignano, Pompei editore, pp. 61–72.

Pescatore, T., Senatore, M. R., Capretto, G., Lerro, G., and Patricelli, G., 1999. Ricostruzione paleoambientale delle aree circostanti l'antica città di Pompei (Campania, Italia) al tempo dell'eruzione del Vesuvio del 79 d.C. *Bollettino Società Geologica Italiana*, **118**(2), 243–254.

Pescatore, T., Senatore, M. R., Capretto, G., and Lerro, G., 2001. Holocene coastal environments near Pompeii before the A.D. 79 eruption of Mount Vesuvius, Italy. *Quaternary Research*, **55**(1), 77–85.

Rolandi, G., Petrosino, P., and McGeehin, J., 1998. The interplinian activity at Somma-Vesuvius in the last 3500 years. *Journal of Volcanology and Geothermal Research*, **82**(1–4), 19–52.

Senatore, M. R., Stanley, J.-D., and Pescatore, T. S., 2004. Avalanche-associated mass flows damaged Pompeii several times before the Vesuvius catastrophic eruption in the 79 C.E. *Annual Meeting of the Geological Society of America, Denver, 7–10 November. Abstracts with Programs*, **36**(5), 308.

Senatore, M. R., Ciarallo, A., Guadagno, F. M., and Grelle, G., 2010. L'applicazione del georadar e della sisimica a rifrazione nella ricostruzione dello scenario naturale antico. Esempi dal sito archeologico di Pompei. In Senatore, M. R., and Ciarallo, A. (eds.), *Scienze naturali e archeologia. Il paesaggio antico: interazione uomo-ambiente ed eventi catastrofici, Museo archeologico nazionale, Napoli 14–16 ottobre*. Roma: Aracne, pp. 211–216.

Senatore, M. R., Ciarallo, A., and Stanley, D., 2014. Pompeii damaged by volcaniclastic debris flows triggered centuries prior to the 79 A.D. Vesuvius Eruption. *Geoachaeology: An International Journal*, **29**, 1–15.

Sigurdsson, H., Carey, S., Cornell, W., and Pescatore, T., 1985. The eruption of Vesuvius in A.D. 79. *National Geographic Research*, **1**(3), 332–387.

POVERTY POINT SITE, LOUISIANA

Anthony L. Ortmann
Department of Geosciences, Murray State University, Murray, KY, USA

Location and description

Poverty Point is a prehistoric community in northeastern Louisiana that was occupied during the Late Archaic period (ca. 3700–3100 BP). The cultural landscape of the site includes five earthen mounds and six concentric, arc-shaped earthen ridges that surround a large, level plaza. The entire Poverty Point earthwork complex covers an area of over 1 km^2.

Geoarchaeology at Poverty Point

Systematic archaeological research at Poverty Point began as early as the middle of the twentieth century, and over the past decade, archaeological investigations at the site have increasingly incorporated geoarchaeological techniques.

Mound A

Excavations in Mound A, the largest mound at the site, were designed to test how the earthwork was constructed, when it was built, and how quickly it was erected (Ortmann and Kidder, 2013). Mound A rises to a height of over 21 m with basal dimensions of approximately 200 m on each side and a volume of nearly 238,000 m^3 of earth. Mound A comprises two distinct sections. The western portion of the mound is a tall (~21 m), cone-shaped feature, while the eastern portion is a shorter (~10 m), flat-topped platform. Excavations have revealed that the mound was built in at least three major stages overlying an Ab soil horizon (a buried A horizon). Thin sections from this Ab horizon have revealed the presence of single-celled freshwater organisms called thecamoebians, indicating this area of the site was a naturally inundated swamp prior to construction of the mound. The first construction stage consists of a thin (6–10 cm) deposit of light gray silt that completely covers the underlying Ab horizon and makes up the base of the platform section of the mound. The second construction stage consists of the tall, western, conical portion of the mound. Soil cores removed near the junction of the cone and platform revealed that a small portion of the eastern edge of the conical portion of the mound overlies the initial construction stage. The final construction stage comprises the bulk of the platform portion of the mound, which was built rapidly in one continuous effort using basket loads of earth and raised to a height of approximately 10 m. This third stage overlies the first construction stage, but also overlaps the second stage near the junction of the cone and platform sections of the mound.

The entire mound appears to have been built quickly. The upper boundary of the first construction stage lacks any evidence for exposure to weathering, such as bioturbation or depositional microlaminae; this evidence suggests that the initial stage was covered by the second and third construction stages almost immediately after it was emplaced. Similarly, micromorphological analysis of the boundaries between the individual basket loads of earth that make up the third construction stage revealed no evidence for bioturbation, size sorting of sediments caused by exposure to rainfall, or the formation of incipient A horizons, which would take time to generate.

Historic climate data for northeastern Louisiana indicate the longest recorded period without measurable rainfall was approximately 1 month. Using these data as a conservative proxy, it seems likely that Mound A was constructed in as little as 30–90 days. Radiocarbon dates from the Ab horizon underlying both the platform and conical sections of the mound indicate Mound A was built sometime after 3261 BP and was likely the last major architectural feature built at Poverty Point.

Earthen ridges and site plaza

Poverty Point's earthen ridges, which demarcate the site's plaza, are traditionally interpreted as habitation areas for the residents of the site. A magnetic gradient survey covering nearly the entire plaza, most accessible portions of the two innermost ridges, as well as large portions of five of the southwestern ridges revealed the presence of numerous magnetic anomalies (Hargrave and Clay, 2014). The earthen ridges are manifest in the magnetic data as linear bands of positive and negative anomalies that probably represent features, discrete deposits of different soils, fired earth cooking balls, fired clay features, hematite artifacts, and other cultural remains with magnetic signatures. Downhole magnetic susceptibility cores suggest that linear positive anomalies associated with the ridges in many areas are flank midden redeposited from the ridge tops and/or upper slopes of the ridges (Dalan et al., 2010). Linear negative magnetic anomalies that occur along the ridge perimeters in many areas are more difficult to interpret. Thirty-nine circular magnetic anomaly complexes ranging in diameter up to about 80 m (with one possible larger outlier) were located near the outer edges of the southern portion of the plaza (Hargrave and Clay, 2014). Interpreted as "post circles," some appear to be composed of discrete anomalies, whereas others appear as continuous circles. Downhole magnetic susceptibility surveys have been used to verify and obtain stratigraphic information on several of the magnetic anomalies and to place test units over different types of circular anomalies. Excavations and magnetic susceptibility surveys within these excavations revealed that the circles are massive post features and large pits variously filled with magnetic and nonmagnetic fill (Greenlee, 2009; Dalan et al., 2010).

Bibliography

Dalan, R. A., Beard, J., Blaha, A., and Cota, A., 2010. *Magnetic susceptibility studies at the poverty point state historic site*. Report submitted to the State of Louisiana, Office of Cultural Development, Division of Archaeology, Baton Rouge, Louisiana.

Greenlee, D. M., 2009. *2009 annual report of the station archaeology program at the poverty point state historic site*. Report submitted to the Division of Archaeology, Louisiana Department of Culture, Recreation, and Tourism, Baton Rouge, Louisiana.

Hargrave, M. L., and Clay, R. B., 2014. *Geophysical investigations at the poverty point site (16WC5), 2006–2011*. Report submitted to the State of Louisiana, Office of Cultural Development, Division of Archaeology, Baton Rouge, Louisiana.

Ortmann, A. L., and Kidder, T. R., 2013. Building Mound A at Poverty Point, Louisiana: monumental public architecture, ritual practice, and implications for hunter-gatherer complexity. *Geoarchaeology*, **28**(1), 66–86.

Cross-references

Magnetometry for Archaeology
Soil Micromorphology
Susceptibility

PRE-CLOVIS GEOARCHAEOLOGY

Andrea Freeman
Department of Anthropology and Archaeology and Earth Science Program, University of Calgary, Calgary, AB, Canada

Definition

Pre-Clovis geoarchaeology involves the geoarchaeological investigation of the material remains of people predating the Clovis complex in the Americas – i.e., before 11,500 ^{14}C years BP (Haynes, 1993; cf., Haynes et al., 2007; Waters and Stafford, 2007; and Waters et al., 2015 for further discussion). Typically, geoarchaeological investigations of this kind must study the context of the material remains embedded within geologic strata and interpret the depositional history and postdepositional alterations at the site and, occasionally, the archaeometric aspects of the finds, such as determining chronology.

Historical background

The geoarchaeological investigation of pre-Clovis sites in the Americas began long before the term "geoarchaeology" was commonly used (Rapp and Gifford, 1982) and before the Clovis projectile point type was formally defined (Cotter, 1937; Howard, 1943). Throughout the history of scientific archaeology in the Americas, archaeological sites indicating potentially deep human antiquity were investigated by throngs of scientists, including geologists (Meltzer, 1983). Among those geologists of the twentieth century called upon to evaluate such finds critically were glaciologist Richard Foster Flint, fluvial geomorphologist Kirk Bryan, and varve chronologist Ernst Antevs. Even the eminent nineteenth-century British geologist Charles Lyell was involved in the early evaluation of the Natchez find (Lyell, 1863, 1873). The principal focus of geoscientific study at these sites was evaluating the context of the remains (mainly fossils and stone tools) within the surrounding stratigraphy and determining, at least initially, the relative (stratigraphic) age of these sites. The goal was to separate solid evidence for a pre-Clovis occupation from poor quality evidence (see Quimby, 1956 on the history of the Natchez pelvis) or even hoaxes like the Calaveras skull in California (Dexter, 1986). Even today, possible pre-Clovis sites initially investigated decades ago are reevaluated by geologists, chronologists (Taylor and Payen, 1979), paleontologists, and archaeologists (Cotter, 1991; Rogers and Martin, 1984). With each newly emerging pre-Clovis contender, new questions arise.

By the 1970s, scientific interest in finding potential pre-Clovis sites had peaked. This intensified concern was perhaps spawned by the eloquent assertion that the timing of an available ice-free landscape in western Canada from ca. 12,000 BP coincidentally fell within the expectations of the new radiocarbon ages on Clovis sites (Haynes, 1964). The investigations of Meadowcroft Rockshelter and the Calico Hills sites, in particular, led to rigorous geoarchaeological examination of the evidence for an "earlier than Clovis" occupation of the Americas. Often, local geologists were called on to help archaeologists interpret the stratigraphy at these sites (Rapp and Gifford, 1982). As the evidence became more complex, C. Vance Haynes, Jr., a skilled geochronologist and geoarchaeologist, emerged as the scientist most called upon to elicit an opinion on the veracity of the finds. Haynes's investigation of Paleo-Indian sites in the San Pedro Valley of Arizona, at Blackwater Draw and Folsom in New Mexico, Hell Gap in Wyoming, and the Tule Springs site in Nevada, gained for him a reputation as an expert in stratigraphy and in the emerging methods of radiocarbon dating. Early experience with limitations of the method caused him to evaluate critically any potential sources of contamination or error. The ensuing, decades-long argument over radiocarbon samples from Meadowcroft Rockshelter created a polarity among scientists that compared with the earlier debate over the existence of an "American Paleolithic" in the late nineteenth and early twentieth centuries (Meltzer, 2005).

Curiously, the mid-1970s was also the time when Monte Verde was discovered in Chile. While archaeologists and geoarchaeologists in North America battled over other pre-Clovis contenders, the excavation of Monte Verde in Chile quietly took place over an 8-year period, conducted by an interdisciplinary team of specialists, including geologists. It took until the 1980s for publications to emerge that promoted Monte Verde as the best candidate for a substantiated pre-Clovis occupation of the Americas, and following similar "expert" visits, Monte Verde was presented to the world as a "verified" pre-Clovis site (Meltzer et al., 1997). New sites continued to emerge throughout the late twentieth century, and geoarchaeologists continued to play a critical role in the evaluation of their age and context. The requisite geoarchaeological research is undertaken by professionals with varied backgrounds and wide-ranging experience; both archaeologists with formal or informal training in the geosciences and geoscientists with formal or informal training in archaeology are involved.

Geoarchaeological studies at pre-clovis sites

Although archaeological sites in Alaska, such as the Nenana and Tanana Valley sites (Powers and Hoffecker, 1989; Holmes, 2001), predate the Clovis occupation, Alaska represents a special case in terms of early occupation of the Americas. During the last glacial advance, it was connected by the Bering Land Bridge (commonly referred to as Beringia) to far eastern Siberia, which possessed its own history of Pleistocene occupation that predated Clovis (Goebel, 1999; Madsen, 2004; Goebel et al., 2008). But Alaska was isolated from unglaciated North America by ice sheets that covered nearly all of Canada. Therefore, the term "pre-Clovis" refers to early human habitations that lie south of the late Pleistocene North American ice sheets, including a widely diverse landscape encompassing North, South, and Central America and the coastlines of those continents.

Pre-Clovis sites that have recently gained the attention of geoarchaeologists include (1) sites in caves and rockshelters (Paisley and Connley Caves in Oregon, South American sites including Pedra Furada in Brazil, Cueva Fell and Cueva del Milodon in Chile, and El Abra and Tibito in Colombia), (2) sites along the western coast of the Americas (underwater caves of Haida Gwaii off the coast of British Columbia and the Channel Islands of California), (3) sites along the sandy coastal plains of eastern North America (Cactus Hill and Saltville in Virginia and Topper in South Carolina), (4) sites in offshore locations (Page-Ladson in Florida, the Hoyo Negro skull in Yucatan, and the Cinmar site off the coast of Virginia), (5) sites in peatlands (the Schaefer and Hebior sites in Wisconsin), and (6) sites in river valleys (the Friedkin site in Texas, Big Eddy in Missouri), dry draws, and eolian landforms in many parts of these continents, where the accumulation of sediments has promoted preservation of archaeological and paleontological specimens.

Also important to note, the recent trends in the investigation of pre-Clovis occupations in the Americas are not restricted to the exploration of newly discovered evidence. Geoarchaeologists have spent considerable effort looking at the evidence recovered from previously studied, yet unresolved sites, as well as exploring the Pleistocene stratigraphy at Clovis and Folsom sites to determine if there is any likelihood of finding pre-Clovis material remains there (Holliday and Meltzer, 1996; Meltzer et al., 2002). A significant aspect in the evaluation of this stratigraphic evidence is the necessary paleoenvironmental reconstruction to determine whether or not the ancient environments in question were favorable for preserving evidence of human activity at these sites.

Emergence of new methods

In addition to the application of accurate chronometric methods to date possible pre-Clovis deposits, another prominent focus of geoarchaeological research at these sites has been the interpretation of whether the ancient late glacial environments were suitable for human mobility and colonization during pre-Clovis time periods (Mandryk, 1990; Erlandson et al., 2007). A pre-Clovis passage for human travel through a corridor free of ice in western Canada was likely temporally and environmentally narrow, and geoarchaeological evidence of such requires detailed reconstruction of glacial geology and age estimates on postglacial features (Holliday, 2009; Freeman, in press). Meanwhile, coastal models for human entry must contend with the environmental viability of a highly mobile seafaring population (Erlandson et al., 2007) and the complexity of deglaciation and sea-level change (Josenhans et al., 1995; Fedje and Christensen, 1999; Fedje et al., 2004).

The recovery of new types of evidence – such as the cordage found at Monte Verde, Chile, and a coprolite from Paisley Caves, Oregon – requires continued and extensive cooperation among geoscientists, chronologists, and biologists.

Bibliography

Cotter, J. L., 1937. The occurrence of flints and extinct animals in pluvial deposits near Clovis, New Mexico, Part IV: Report of the excavations at the gravel pit in 1936. *Proceedings of the Philadelphia Academy of Natural Sciences*, **89**, 1–16.

Cotter, J. L., 1991. Update on Natchez man. *American Antiquity*, **56**(1), 36–39.

Dexter, R. W., 1986. Historical aspects of the Calaveras skull controversy. *American Antiquity*, **51**(2), 365–369.

Erlandson, J. M., Graham, M. H., Bourque, B. J., Corbett, D., Estes, J. A., and Steneck, R. S., 2007. The kelp highway hypothesis: marine ecology, the coastal migration theory, and the peopling of the Americas. *The Journal of Island and Coastal Archaeology*, **2**(2), 161–174.

Fedje, D. W., and Christensen, T., 1999. Modeling paleoshorelines and locating early Holocene coastal sites in Haida Gwaii. *American Antiquity*, **64**(4), 635–652.

Fedje, D. W., Mackie, Q., Dixon, E. A., and Heaton, T. H., 2004. Late Wisconsin environments and archaeological visibility on the northern Northwest Coast. In Madsen, D. B. (ed.), *Entering America: Northeast Asia and Beringia Before the Last Glacial Maximum*. Salt Lake City: University of Utah Press, pp. 97–138.

Freeman, A. K. L., in press. Why the ice-free corridor is still relevant to the peopling of the New World. In Kornfeld, M., and Huckell, B. (eds.), *Stones, Bones, and Profiles: Exploring Archaeological Context, Early American Hunter-Gatherers, and Bison*. Boulder: University of Colorado Press.

Goebel, T., 1999. Pleistocene human colonization of Siberia and peopling of the Americas: an ecological approach. *Evolutionary Anthropology*, **8**(6), 208–227.

Goebel, T., Waters, M. R., and O'Rourke, D. H., 2008. The Late Pleistocene dispersal of modern humans in the Americas. *Science*, **319**(5869), 1497–1502.

Haynes, C. V., Jr., 1964. Fluted projectile points: their age and dispersion: stratigraphically controlled radiocarbon dating provides new evidence on peopling of the New World. *Science*, **145**(3639), 1408–1413.

Haynes, C. V., Jr., 1993. Clovis-Folsom geochronology and climatic change. In Soffer, O., and Praslov, N. D. (eds.), *From Kostenki to Clovis: Upper Paleolithic Paleo-Indian Adaptations*. New York: Plenum Press, pp. 219–236.

Haynes, G., Anderson, D. G., Ferring, C. R., Fiedel, S. J., Grayson, D. K., Haynes, C. V., Jr., Holliday, V. T., Huckell, B. B., Kornfeld, M., Meltzer, D. J., Morrow, J., Surovell, T., Waguespack, N. M., Wigand, P., and Yohe, R. M., II, 2007. Comment on "Redefining the Age of Clovis: Implications for the Peopling of the Americas". *Science*, **317**(5836), 320.

Holliday, V. T., 2009. Geoarchaeology and the search for the first Americans. *Catena*, **78**(3), 310–322.

Holliday, V. T., and Meltzer, D. J., 1996. Geoarchaeology of the Midland (Paleoindian) site, Texas. *American Antiquity*, **61**(4), 755–771.

Holmes, C. E., 2001. Tanana River valley archaeology circa 14,000 to 9000 B.P. *Arctic Anthropology*, **38**(2), 154–170.

Howard, E. B., 1943. Folsom and Yuma problems. *Proceedings of the American Philosophical Society*, **86**(2), 255–259.

Josenhans, H. W., Fedje, D. W., Conway, K. W., and Barrie, J. V., 1995. Post glacial sea levels on the western Canadian continental shelf: evidence for rapid change, extensive subaerial exposure, and early human habitation. *Marine Geology*, **125**(1–2), 73–94.

Lyell, C., 1863. *The Geological Evidences of the Antiquity of Man; with Remarks on Theories of the Origin of Species by Variation*. London: John Murray.

Lyell, C., 1873. *The Geological Evidence of the Antiquity of Man with an Outline of Glacial and Post-Tertiary Geology and Remarks on the Origin of Species with Special Reference to Man's First Appearance on the Earth*, 4th edition revised. London: John Murray.

Madsen, D. B. (ed.), 2004. *Entering America: Northeast Asia and Beringia Before the Last Glacial Maximum*. Salt Lake City: University of Utah Press.

Mandryk, C. A., 1990. Could humans survive the ice-free corridor?: late-glacial vegetation and climate in west central Alberta. In Agenbroad, L. D., Mead, J. I., and Nelson, L. W., (eds.), *Megafauna and Man: Discovery of America's Heartland*. Scientific Papers 1. Hot Springs, South Dakota: Mammoth Site of Hot Springs, South Dakota, pp. 67–79.

Meltzer, D. J., 1983. The antiquity of man and the development of American archaeology. *Advances in Archaeological Method and Theory*, **6**, 1–51.

Meltzer, D. J., 2005. The seventy-year itch: controversies over human antiquity and their resolution. *Journal of Anthropological Research*, **64**(4), 433–468.

Meltzer, D. J., Grayson, D. K., Ardila, G., Barker, A. W., Dincauze, D. F., Haynes, C. V., Mena, F., Núñez, L., and Stanford, D. J., 1997. On the Pleistocene antiquity of Monte Verde, southern Chile. *American Antiquity*, **62**(4), 659–663.

Meltzer, D. J., Todd, L. C., and Holliday, V. T., 2002. The Folsom (Paleoindian) type site: past investigations, current studies. *American Antiquity*, **67**(1), 5–36.

Powers, W. R., and Hoffecker, J. F., 1989. Late Pleistocene settlement in the Nenana valley, central Alaska. *American Antiquity*, **54**(2), 263–287.

Quimby, G. I., 1956. The locus of the Natchez pelvis find. *American Antiquity*, **22**(1), 77–79.

Rapp, G., Jr., and Gifford, J. A., 1982. Archaeological geology: at the interface of geology and archaeology a new discipline is taking shape, with a wide variety of research methods and an eclectic approach to data. *American Scientist*, **70**(1), 45–53.

Rogers, R. A., and Martin, L. D., 1984. The 12 Mile Creek site: a reinvestigation. *American Antiquity*, **49**(4), 757–764.

Taylor, R. E., and Payen, L. A., 1979. The role of archaeometry in American archaeology: approaches to the evaluation of the antiquity of *Homo sapiens* in California. *Advances in Archaeological Method and Theory*, **2**, 239–283.

Waters, M. R., and Stafford, T. W., Jr., 2007. Redefining the age of Clovis: implications for the peopling of the Americas. *Science*, **315**(5815), 1122–1126.

Waters, M. R., Stafford, T. W., Jr., Kooyman, B., and Hills, L. V., 2015. Late Pleistocene horse and camel hunting at the southern margin of the ice-free corridor: reassessing the age of Wally's Beach, Canada. *Proceedings of the National Academy of Sciences*, **112**(14), 4263–4267.

PRIVIES AND LATRINES

Richard I. Macphail
Institute of Archaeology, University College London, London, UK

Synonyms

Cesspits, garderobes; Human waste and coprolites

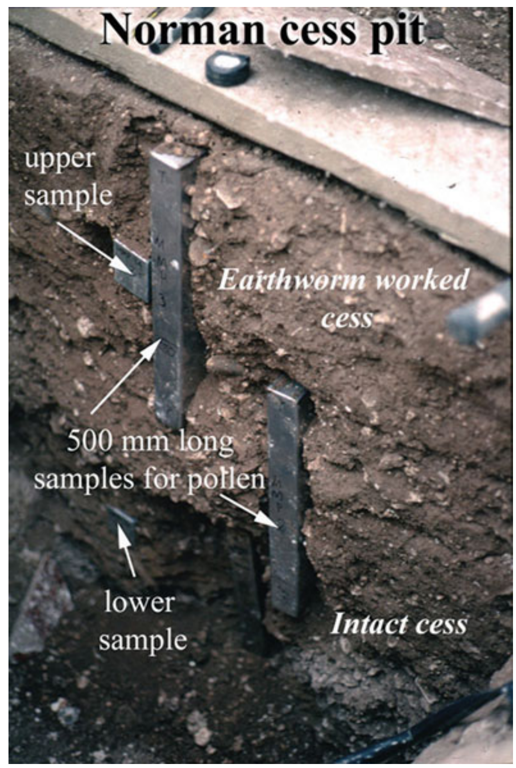
Definition

Privies and latrines are associated with the generation, disposal, and storage of human waste, often in pits and soakaways termed cesspits.

Introduction

Wherever humans congregate there is the need to manage their fecal waste, and such waste can therefore serve as evidence of human occupation, usually preserved as a coprolite, coprolite fragments, or as totally or partially mineralized accumulations in cesspits and drains from latrines (Figures 1 and 2). Cesspit deposits have more commonly been studied through their biological remains, insects, parasite eggs, and food residues. These fills, however, can also be regarded as a specific anthropogenic sediment type, and they have been investigated by soil micromorphology (Macphail and Goldberg, 2010) and associated microprobe and bulk chemical analyses. The key chemical is phosphorus, which with H, C, N, and O is a primary element in the biosphere and is concentrated in fecal waste. Sometimes, this waste is collected in a toilet bucket, the contents of which are disposed of elsewhere (cf. "night soil"). Our studies have shown that where humans are concentrated, this will be mirrored in the amount of human waste present. This can stain and contaminate earlier deposits, and completely skew chemical analyses of these earlier deposits if this contamination is unrecognized. Channels and voids in juxtaposed soils and sediments can be lined with phosphate from cesspit leakage; bulk analyses may show anomalously high phosphate contents. It is therefore important to be able to recognize mineralized fecal material, be it as layered in situ cess, intact coprolites, coprolite/cess fragments, or simply as secondary concentrations of phosphate minerals. In addition, it is important to be able to differentiate human cess and coprolites from other mineralized fecal material, especially that of omnivores such as canids (e.g., dogs) and pigs, which also scavenge sites of human occupation. Fecal material of human origin has been studied from the intestines of mummies (Holden, 1990) and from convincing cesspit and latrine channel contexts where eggs of parasitic nematodes specific to humans and other fecal indicators (bran, mineralized fly pupae) have been found through palynology, parasitology, and macrofossil analyses. In addition, some specific reference material was first identified employing specific nematode egg extractions and analyses (Kenward and Hall, 1995).

Privies and Latrines, Figure 1 Monkton (Thanet, Kent, UK): Norman medieval cesspit cut into chalk (see Figure 2).



Privies and Latrines, Figure 2 Monkton (Thanet, Kent, UK): fill of Norman cesspit, composed of intact layered cess at the base and earthworm-worked dispersed and oxidized cess at the *top*. *Upper* and *lower* Kubiena box samples are shown (see Figure 1 and Table 1).

Human coprolites

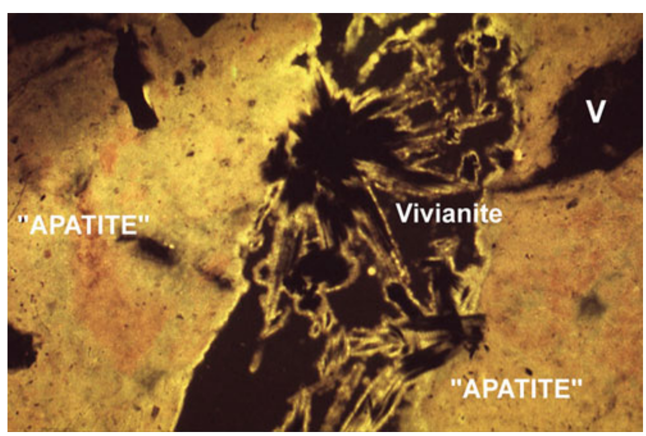
Examples from Saxon Maiden Lane (the Strand, London) and Viking Coppergate (York), identified on the basis of human nematode egg content (appropriate size range of human whip worm *Trichuris* eggs found by C. De Rouffignac and A. Jones, respectively, pers. comm.), have been analyzed in detail (full analyses in Macphail and Goldberg, in prep). Chemically, the Maiden Lane coprolite has a dominantly calcium phosphate content, and its autofluorescence under blue light (BL) fluorescence microscopy suggests a probable apatite mineralogy. Autofluorescent materials – bone apatite, plant cellulose – when irradiated with short-wave radiation, such as blue light, emit radiation with a longer wave length ("luminescence"), but only as long as the excitation lasts (Stoops, 2003). Microprobe produced the following data: 18–34 % Ca, 8–14 %P, 0.6–3.5 % Fe, 0.2–4.4 % Mn, <0.1 % Al, <0.1 % K, 0.1 % Mg, 0.0–0.1 % Si; $n = 7$). It has a yellowish brown color under plane polarized light (PPL; Figure 3) and is isotropic (under crossed polarized light, XPL), with reddish to whitish colors under oblique incident light (OIL) (Courty et al., 1989: Plate IVa). It shows low to high autofluorescence (BL). Reddish to blackish streaks seem to relate to iron and manganese staining of amorphous organic matter, presumably of dietary origin. The Coppergate Viking coprolite is exceedingly rich in dietary residues, including fine- and medium-sized bone fragments, ubiquitous plant fragments including articulated sheets of phytoliths (cereal bran), and legume testa (seed cases) (Macphail et al., 1990). A blackberry seed is also present. These findings testify to a broad diet. When employing blue light, non-autofluorescent *Trichuris* eggs can be seen as "negatives" within the autofluorescent matrix; secondary iron phosphate occurs as blue vivianite crystals or "ghosts" within the coprolite, and these are also non-autofluorescent (Figure 4). These findings helped the identification of coprolite fragments elsewhere, for example, at the large Late Bronze Age/Early Iron Age site of Potterne, Wiltshire, where the presence of roundworm (*Ascaris*, P. Wiltshire, pers. comm.) and other nematode eggs was noted in the thin section sample, alongside embedded cereal remains and fine bone.

It is likely that the presumed hydroxylapatite forming mineralized cess and coprolites is in fact carbonate hydroxylapatite, as it is found so often as a secondary mineral in archaeological sites employing FTIR studies (Karkanas et al., 2002; Weiner, 2010, 83–84; Karkanas 2011, pers. comm.). It can also be noted that an example of bone-eating carnivore scat from the Cretaceous included minute bone, teeth, and plant remains, and vesicular pseudomorphs of fine organic matter, some interpreted as relict fecal bacteria, were embedded in francolite (Ca-P dominated carbonate fluorapatite) because of an intake of dietary calcium phosphate (Hollocher et al., 2010).

Comparing canid and pig coprolites

In the field, human coprolites are yellowish brown, while dog coprolites are often whitish and may contain large bone fragments. In thin section, dog coprolites can be whitish, or grayish, with very fine blackish speckles (bacterial activity? M-A Courty, pers. comm.), and they are whitish under OIL. They also show a marked autofluorescence under BL. Bone inclusions often show grayish (digestive) leaching, and such bone fragments occur within occupation deposits where dogs have been scavenging. Dogs also ingest silt (when drinking), fur, or wool producing pseudomorphic voids. For example, sheep bones showed gnawing at Saxon West Heslerton, North Yorkshire, UK, where many dog coprolites included wool-size voids. Another characteristic is the

Privies and Latrines, Figure 3 Maiden Lane (The Strand, London, UK): photomicrograph of Middle Saxon human coprolite (according to human nematode egg analysis); it has a pale yellow matrix of probable Ca-P apatite according to microprobe analysis, with brown and blackish Fe and Mn staining of indeterminate plant food residues. Voids likely record trapped gas. Plane polarized light (PPL), frame width is ~5.5 mm.



Privies and Latrines, Figure 4 Coppergate (York, UK): photomicrograph of Viking coprolite (according to human nematode egg analysis); the "apatite" matrix is autofluorescent under blue light, and this material has coated iron phosphate vivianite and ghosts of vivianite, which also formed under anaerobic conditions. Blue light illumination, frame width is ~0.6 mm.

Privies and Latrines, Table 1 Medieval cess from Monkton (Kent), and the London Guildhall and Spitalfields sites, London; magnetic susceptibility, bulk chemistry, and microprobe data

	LOI %	P_2O_5 (ppm)	Phosphate-P (mg g^{-1})	χ ($\times 10^{-8}$ m^3 kg^{-1})	pH, CO_3	Heavy metals (μg g^{-1})	Microprobe
Monkton[a] upper fill	4.7	700		82.0			
Monkton[a] lower fill	19.6	>4,780		11.0			
Guildhall[b]	28.0		52.6	5.50 (=0.260 % χ_{conv})	6.1, < 0.1 %	132 Pb, 468 Zn, 222 Cu	*6.57 % P, 22.0 % Ca
Spitalfields[2]	51.6		72.4	0.388 (=0.285 % χ_{conv})		266 Pb, 809 Zn, 172 Cu	**3.44 % P, 7.87 % Ca

LOI loss on ignition
χ magnetic susceptibility
Microprobe full data
*Guildhall = 0.025 % Si, 0.017 % Al, 6.57 % P, 22.0 % Ca, 0.086 % Na, 0.111 % Mg, 0.326 % Mn, 0.507 % S, 0.74 % Fe, and 0.021 % K; vertical line analysis, specifically through Ca-P cess layer ($n = 4$)
**Spitalfields = 2.46 % Si, 0.049 % Al, 3.44 % P, 7.87 % Ca, 0.017 % Na, 0.330 % Mg, 0.088 % Mn, 0.587 % S, 0.745 % Fe, 0.305 % K, 0.033 % Pb, 0.022 % Zn, and 0.010 Cu, overall Line analysis ($n = 47$)
NB: Analyses by
[a]Johan Linderholm, Environmental Archaeology Lab (MAL), University of Umeå, Sweden
[b]John Crowther, University of Lampeter Archaeological Services, University of Wales Trinity Saint David, UK

amount of vesicles present, caused by trapped gas, which is also a trait of hyena coprolites (Horwitz and Goldberg, 1989).

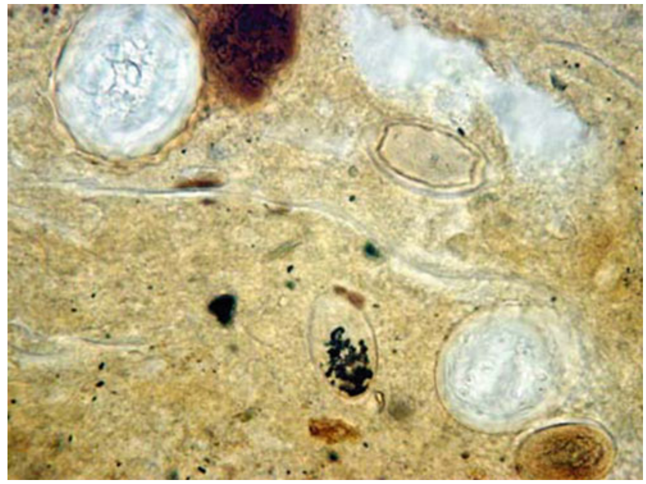
Generally, wild pig feces and coprolites should be easily distinguishable from human material, because they are dominantly composed of amorphous and fragmentary plant material, much less phosphate-rich, and often reveal very poorly, or non-autofluorescent matrix material (Courty et al., 1994). This is also the case for modern pigs fed a cereal diet, for example. In the archaeological record, however, it seems likely that some deposits include phosphate-rich pig fecal deposits, because they were fed/scavenged on meat and bone-rich waste. Such deposits, however, seem to be non-autofluorescent and contain Fe and Mn in addition to Ca and P. Pig feces are less phosphate-rich and include high quantities of plant remains when fed purely a vegetarian diet.

Cess

This occurs as in situ layered deposits in cesspits, which are located beneath the privy or latrine itself, or in the channels that drain privies. These are best preserved at the base of the fills, whereas upper deposits are more likely to have been subject to oxidation and biological working. This post-depositional weathering is discussed below, after some pristine deposits are described. Three cases are presented. These are a latrine drain fill at the London Guildhall eleventh-century settlement site, a twelfth century cesspit privy fill at rural Monkton, Kent (see Figures 1 and 2), and a late medieval (AD 1400–1480) cess-filled pit at the priory and hospital of St. Mary Spital (Spitalfields), London. Complementary environmental analyses found *Ascaris* eggs, mineralized fly pupae, and bran residues at Monkton, and the nematode eggs, of *Ascaris* and *Capillaria*, were identified within the thin section of the Guildhall cess (M. Robinson and P. Wiltshire, pers. comm.); palynology of the Spitalfields cesspit indicated human fecal inputs (R. Scaife, pers. comm.). Although bulk analyses of this cess were carried out at different times, these show a consistent high organic (LOI) and very high phosphate content and very low magnetic susceptibility (Table 1). Heavy metal concentrations of Zn and Cu in particular were noted. Such concentrations are of biological origin and are not related to industrial activity (e.g., as corroborated by statistical analysis at the Guildhall site; Bowsher et al., 2007; Macphail et al., 2007).

In thin section, cess is often layered or occurs as fragmented layers. It is commonly yellow to finely speckled yellow (PPL), isotropic (XPL), dark yellowish brown (OIL), and strongly autofluorescent under BL and often includes food remains similar to those found in human coprolites, such as sheets of articulated phytoliths (cereal bran), legume testa, fine bone, and nematode eggs (Macphail and Goldberg, 2010: Figure 18) (Figures 5 and 6). This visible organic content is consistent with bulk analyses; microprobe analyses and associated Ca-P mapping show that cess is probably formed of apatite. Localized anaerobic and acidic conditions in cesspits are also believed to be responsible for the formation of Ca-P mineralized seed remains (as internal casts) (Carruthers, 2000). This is consistent with a lack of magnetic susceptibility enhancement and carbonate. Poorly preserved cess deposits have been observed at a number of sites, where the organic component has become oxidized, and the mineralized material has become finely fragmented by soil

Privies and Latrines, Figure 5 London Guildhall (London, UK): scan of 150 mm long thin section (977-1) through ditch fill within the Early Medieval (eleventh to twelfth century AD) settlement. A 20 mm thick series of yellow Ca-P cess layers toward the *top* of the thin section occur within generally organic fill composed of stabling residues and wood fragments.

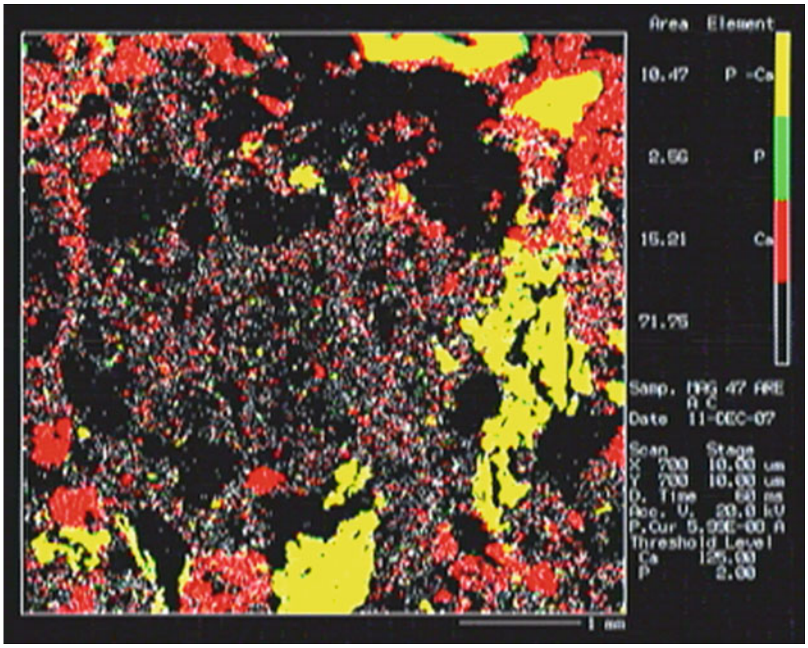


Privies and Latrines, Figure 6 London Guildhall (London, UK): photomicrograph of sample 977-1 (see Figure 5) detailing cess. Yellow phosphate embeds a number of unidentified nematode eggs (see Table 1). PPL, frame width is 0.23 mm.

fauna such as earthworms. At Monkton, intact cess was examined from a depth of 157 cm (Figure 2, lower fill). A second sample was studied from 45 cm (upper fill), where a much lower organic and phosphate content, but higher magnetic susceptibility, were recorded (Table 1). Here, a scatter of fine BL-autofluorescent cess fragments occurred within earthworm excrements.

At all three examples, pure Ca-P cess occurs within other dumped materials. At the Guildhall and Spitalfields, this included herbivore stabling waste, which itself is rich in plant material and moderately phosphate-rich (Figures 5 and 6). The Monkton deposits also included layers of charred and ashed stabling waste. Here, it can be considered that the addition of ash was a way of "sweetening" the cesspit. In theory, the contents of the toilet bucket were also "sweetened" with ash, and it can be noted that remains of such "night soil" can occur as amorphous phosphate embedding calcite ash crystals and charcoal. When such latrine-waste deposits are found in urban contexts, for example, in Late Roman London and Canterbury, it could suggest that there has been a breakdown in urban ("civilized") organization. On the other hand, this may also indicate horticultural manuring with night soil. Nevertheless, bulk, micromorphological, and microprobe studies of night soil disposal in a Late Saxon street in Canterbury, UK, and at a seventh- to eighth-century settlement at St. Julien, Tours, France, found phytoliths, plant tissues, ash, and charcoal embedded within a BL-autofluorescent Ca-P matrix, which was also present in association with non-autofluorescent amorphous Ca-P-Fe, in which blue vivianite had crystallized (Galinié et al., 2007) (see also Figure 7). In fact, amorphous phosphate, commonly including vivianite, is a good indicator of phosphatic waste disposal in general, but it may have other origins beyond latrine waste (e.g., animal waste and residues from weathered ash, bone). As such, this material has to be interpreted with caution.

Medieval castle garderobes are another source of cess. At Pevensey Castle (East Sussex, UK), occupation deposits were increasingly yellow stained upwards because of the effect of local (garderobes/cesspits) latrine outflow associated with the Norman keep (Trench 2). Microprobe confirmed Fe-Ca-P staining of soils (1.79 % Fe, 0.486 % Ca, 1.17 % P; Macphail, 2011). At the Tower of London (London, UK), garderobes drained into the moat, and although the moat fills are sediment-diluted, phosphate concentrations were sufficiently elevated alongside a very strong relationship with LOI ($r = 0.821$, $p < 0.001$) indicating inputs of organic phosphate (e.g., cess) in both thirteenth-century (Edward I) and post-medieval contexts (Macphail and Crowther, 2004). There were also strong statistical relationships between LOI and heavy metals (Cu, Pb, and Zn), possibly also implying a fecal matter source for these, although unlike

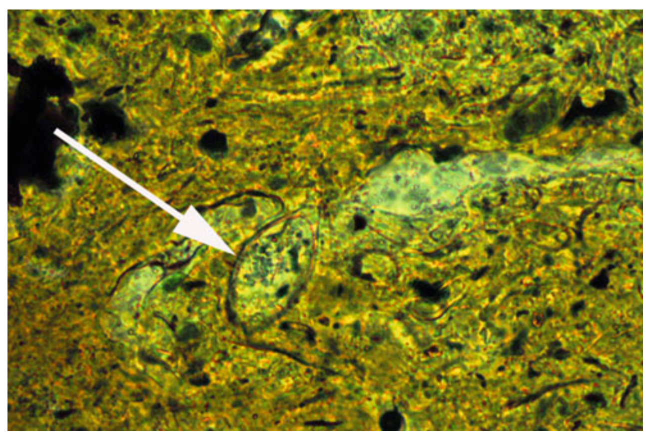


Privies and Latrines, Figure 7 Măgura, southern Romania: early Neolithic pit fill (sample 03–47); microprobe map of the distribution of Ca and P; around the edges of central burrow-mixed soil are yellow fragments of Ca-P cess (see Figure 8). Scale bar is 1 mm.

the Guildhall site (see above) lead roofing and stone "cementation," and industrial activities (Royal Ordnance, use/manufacture of brass; Cu-Zn) appear to be more important sources.

General occurrence of ancient fecal waste

Caution must be similarly employed when fine (50–500 μm) autofluorescent "cess" and/or coprolite fragments occur within occupation sediments, as these could also be of fragmented omnivore animal origin. Such "undifferentiated" fecal remains can be ubiquitous in occupation deposits including house floors and may simply record latrine-waste spillage and tracking-in. Finely layered floor deposits at the Spitalfields contemporary with the cesspit included such tracked-in fecal material. Less accidental occurrences may often persist as small or large coprolites within abandoned structures, such as the Maiden Lane and Coppergate coprolites. All kinds of pits, disused wells, midden spreads, etc., may include coprolitic waste. For example, likely human cess fragments were found in Early Neolithic pits in China (Huizui), Hungary, and Romania, for example, and the last one included a *Trichuris* egg (Macphail et al., 2008) (Figures 7 and 8). Surely, this is not accidental, but a form of human waste management.



Privies and Latrines, Figure 8 Măgura, southern Romania: early Neolithic pit fill (sample 03–47); photomicrograph of probable *Trichuris* nematode egg (*arrow*) embedded in cess. PPL, frame width is ~0.23 mm.

Summary

Deposits associated with privies and latrines are a specific sediment type that can be recognized from their chemistry and micromorphology and occasionally inclusion of recognizable food residues and parasite eggs. The probable apatite mineralogy of cess and human coprolites is recognized from their blue light autofluorescence. Cess, sensu stricto, is usually characterized using techniques such as microprobe, and human coprolites are differentiated from those of other omnivores such as dogs and pigs.

Bibliography

Bowsher, D., Dyson, T., Holder, N., and Howell, I., 2007. *The London Guildhall: The Archaeological History of a Neighbourhood from Early Medieval to Modern Times*. London: Museum of London Archaeology Service. Monograph 36.

Carruthers, W. J., 2000. Mineralised plant remains. In Lawson, A. J. (ed.), *Potterne 1982-5. Animal Husbandry in Later Prehistoric Wiltshire*. Salisbury: Trust for Wessex Archaeology. Wessex Archaeology Report, Vol. 17, pp. 72–84.

Courty, M. A., Goldberg, P., and Macphail, R. I., 1989. *Soils and Micromorphology in Archaeology*. Cambridge: Cambridge University Press.

Courty, M. A., Goldberg, P., and Macphail, R. I., 1994. Ancient people – lifestyles and cultural patterns. In Etchevers, J. D. (ed.), *Transactions of the 15th World Congress of Soil Science, Mexico*. Acapulco: International Society of Soil Science, Vol. 6A, pp. 250–269.

Galinié, H., Lorans, E., Macphail, R. I., Seigne, J., Fondrillon, M., Laurent, A., and Moreau, A., 2007. La fouille du square Prosper-Mérimée. The excavation in Prosper-Mérimée Square. In Galinié, H. (ed.), *Tours, antique et médiéval: lieux de vie, temps de la ville, 40 ans d'archéologie urbaine. Supplément à la revue archéologique du centre de la France, 30: spécial de la collection Recherches sur Tours*. Tours: Revue Archéologique du Centre de la France (FERACF), pp. 171–180.

Holden, T. G., 1990. *Taphonomic and Methodological Problems in Reconstructing Diet from Ancient Human Gut and Faecal Remains*. Unpublished PhD dissertation, London, University College London.

Hollocher, K. T., Hollocher, T. C., and Rigby, J. K., Jr., 2010. A phosphatic coprolite lacking diagenetic permineralization from the Upper Cretaceous Hell Creek Formation, northeastern Montana: importance of dietary calcium phosphate in preservation. *PALAIOS*, **25**(2), 132–140.

Horwitz, L. K., and Goldberg, P., 1989. A study of Pleistocene and Holocene hyaena coprolites. *Journal of Archaeological Science*, **16**(1), 71–94.

Karkanas, K., Rigaud, J.-P., Simek, J. F., Albert, R. M., and Weiner, S., 2002. Ash, bones and guano: a study of the minerals and phytoliths in the sediments of Grotte XVI, Dordogne, France. *Journal of Archaeological Science*, **29**(7), 721–732.

Kenward, H. K., and Hall, A. R., 1995. *Biological Evidence from Anglo-Scandinavian Deposits at 16–22 Coppergate. The Archaeology of York*. York: York Archaeological Trust and Council for British Archaeology, Vol. 14, fascicle 7.

Macphail, R. I., 2011. Soil micromorphology. In Fulford, M., and Rippon, S. (eds.), *Pevensey Castle, Sussex. Excavations in the Roman Fort and Medieval Keep, 1993–95*. Salisbury: Wessex Archaeology. Wessex Archaeology Report, Vol. 26, pp. 109–121.

Macphail, R. I,, and Crowther, J., 2004. Tower of London Moat: sediment micromorphology, particle size, chemistry and magnetic properties. In Keevil, G. (ed.), *Tower of London Moat Excavation*. Historic Royal Palaces Monograph 1. Oxford: Oxford Archaeology, pp. 41–43, 48–50, 78–79, 82–83, 155, 183–186, 202–204 and 271–284.

Macphail, R. I., and Goldberg, P., in prep. *Applied Soils and Micromorphology in Archaeology*. Cambridge: Cambridge University Press.

Macphail, R. I., and Goldberg, P., 2010. Archaeological materials. In Stoops, G., Marcelino, V., and Mees, F. (eds.), *Interpretation of Micromorphological Features of Soils and Regoliths*. Amsterdam: Elsevier, pp. 589–622.

Macphail, R. I., Courty, M.-A., and Goldberg, P., 1990. Soil micromorphology in archaeology. *Endeavour, New Series*, **14**(4), 163–171.

Macphail, R. I., Crowther, J., and Cruise, G. M., 2007. Microstratigraphy: soil micromorphology, chemistry and pollen. In Bowsher, D., Dyson, T., Holder, N. and Howell, I. (eds.), *The London Guildhall. An Archaeological History of a Neighbourhood from Early Medieval to Modern Times*. London: Museum of London Archaeological Service, pp. 18, 25–16, 35, 39, 55–56, 57, 59, 76, 90, 97, 98, 134, 154–155, 428–430.

Macphail, R. I., Haită, C., Bailey, D. W., Andreescu, R., and Mirea, P., 2008. The soil micromorphology of enigmatic Early Neolithic pit-features at Măgura, southern Romania. *Asociația Română de Arheologie. Studii de Preistorie*, **5**, 61–77.

Stoops, G., 2003. *Guidelines for Analysis and Description of Soil and Regolith Thin Sections*. Madison: Soil Science Society of America.

Weiner, S., 2010. *Microarchaeology. Beyond the Visible Archaeological Record*. Cambridge: Cambridge University Press.

Cross-references

Experimental Geoarchaeology
Fourier Transform Infrared Spectroscopy (FTIR)
York

R

RADIOCARBON DATING

R. E. Taylor
Emeritus, Department of Anthropology, University of California, Riverside, Riverside, CA, USA

Synonyms

^{14}C dating; Carbon-14 dating

Definition

Radiocarbon is a naturally occurring radioactive isotope of carbon used as the basis for a nuclear decay method of inferring age for terminal Pleistocene and Holocene Age organic materials.

Radiocarbon time scale provides a common chronometric time scale of worldwide applicability on a routine basis using the radiocarbon (^{14}C) method. It is effective in age determination for the terminal Pleistocene and, except for the last few centuries, all of the Holocene.

Introduction

Carbon contains three naturally occurring isotopes, two of which are stable (^{12}C, ^{13}C) and one (^{14}C or radiocarbon) which is, at the nuclear level, naturally unstable or radioactive and decays with a half-life of ~5,700 years. Radiocarbon (^{14}C) dating is an isotopic or nuclear decay method of inferring age for organic materials, and it provides a common chronometric time scale of worldwide applicability for the late Quaternary. The technique is widely viewed as the geochronological "gold standard" from the perspective of its potential ability to provide generally accurate and relatively precise chronometric age assignments for a variety of organics for that time interval. Radiocarbon measurements can be obtained on a broad spectrum of carbon-containing samples including charcoal, wood, marine shell, and bone. Using conventional decay or beta counting, the ^{14}C method can be routinely employed within the age range of about 300 years ago to between 40,000 and 50,000 years ago for sample sizes between 1 and 10 g of carbon. With isotopic enrichment and larger sample sizes, ages up to 75,000 years have been measured using decay counting (Taylor, 1996, 2001).

The ^{14}C dating technique was developed at the University of Chicago immediately following World War II by Willard F. Libby (1908–1980) and his collaborators James R. Arnold and Ernest C. Anderson (Arnold and Libby, 1949; Libby et al., 1949). Libby received the Nobel Prize in Chemistry in 1960 for developing the method (Arnold, 1981).

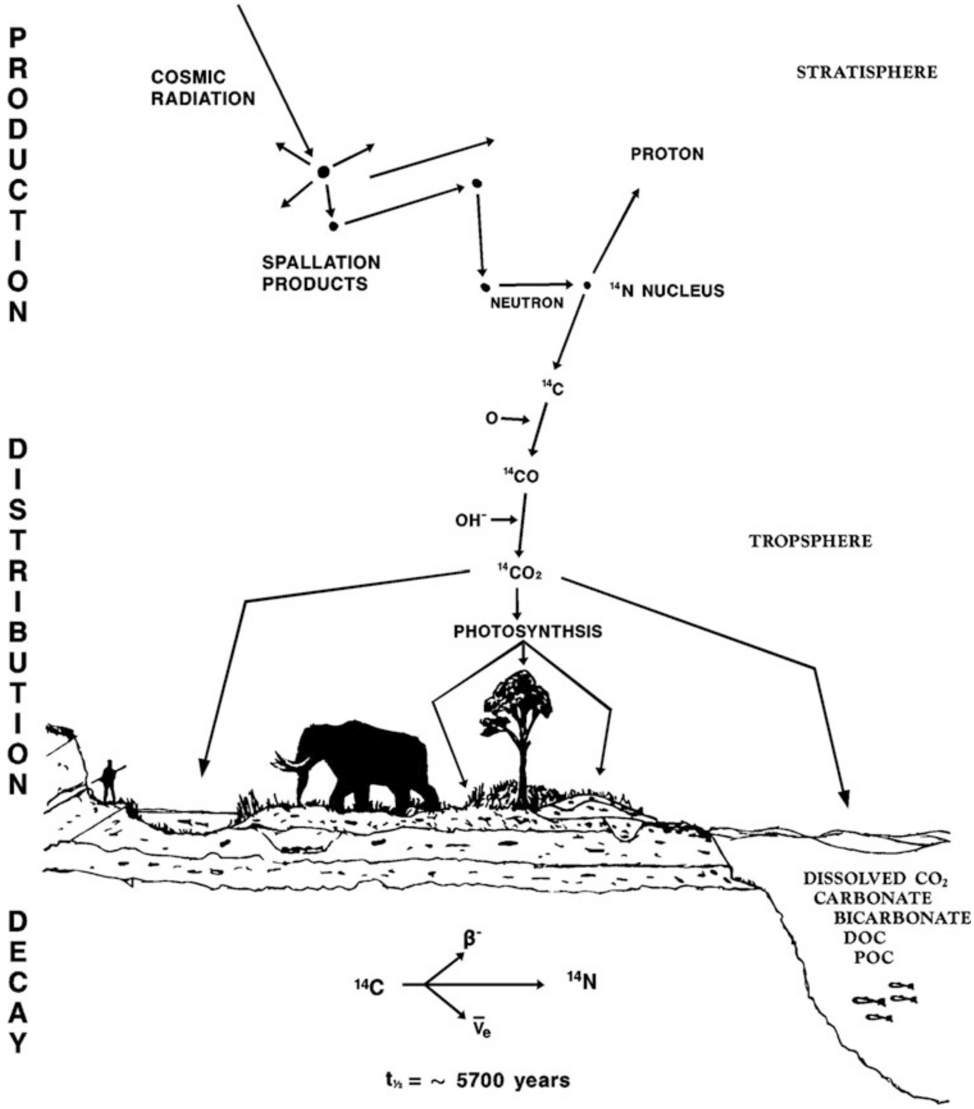
Since the 1970s, the development of accelerator mass spectrometry (AMS) for direct or ion counting of ^{14}C permits measurements to be obtained routinely on samples of 0.5–1 mg of carbon – and with additional effort on as little as 20–100 μg of carbon – with ages up to 40,000–50,000 years. In the future, the use of AMS technology may permit a significant extension of the ^{14}C time frame to as much as 80,000 years if routine strategies can be developed and consistently employed to exclude microcontamination in samples (Knezovich et al., 2007; Calcagnile et al., 2010; Chen et al., 2011).

Dating model

Carbon reservoirs

Carbon-containing compounds in a wide variety of forms are distributed throughout the Earth's highly diverse atmospheric, terrestrial, and hydrological (primarily marine, but also freshwater) environments. On different time scales and by a variety of physical or chemical mechanisms, these compounds are cycled through various actively exchanging carbon reservoirs, which are natural accumulations of carbon (i.e., forests or oceans). The carbon cycle processes are dominated by the operation

A.S. Gilbert (ed.), *Encyclopedia of Geoarchaeology*, DOI 10.1007/978-1-4020-4409-0,



Radiocarbon Dating, Figure 1 Radiocarbon dating model: production, distribution, and decay of ^{14}C (Adapted from Figure 1 in Taylor (2001)).

of two major intersecting and interacting physical and geochemical systems.

The first system involves photosynthetic cycles utilizing several complex biochemical pathways involving the fixation of atmospheric carbon dioxide (CO_2) in plant materials, incorporation of a small portion of plant biomass into animal tissue, and subsequent decomposition with the release of carbon dioxide (CO_2) and methane (CH_4) back into the atmosphere. The second system involves the cycling of various chemical species – including carbonates, bicarbonates, dissolved inorganic carbon (DIC) in the form of carbon dioxide, and dissolved and particulate organic carbon (DOC and POC) – primarily between the oceans and atmosphere. Various chemical and physical processes including the deposition of carbonates in terrestrial and oceanic sediments and volcanic activity are also involved in the operation of the carbon cycle on much longer geologic time scales (Trumbore, 2000).

Radiocarbon production, distribution, and decay

The basis of the use of ^{14}C as a dating isotope is illustrated in Figure 1 in terms of its production, distribution, and decay. The production of ^{14}C is a secondary effect of cosmic-ray interactions with the nuclei of atmospheric gas molecules. Primary cosmic rays are mostly composed of protons (hydrogen nuclei) and helium nuclei which have been accelerated to extremely high energies. Because they are charged particles, many are deflected by the various components of the magnetic field of our sun and by the Earth's dipole magnetic field. However, a small percentage of these particles, many of which continue to possess very high energies, reach the top of the Earth's atmosphere. These primary particles produce a cascade of secondary particles. Collisions of both primary and secondary particles in the stratosphere with the nuclei of atmospheric gas molecules yield a range of products through cosmic-ray spallation, including free neutrons (L'Annunziata, 2007, 399–426).

The free neutrons continue to interact with other particles, losing energy in the process. As these particles reach appropriate energies, they can react with the nucleus of ^{14}N to form ^{14}C. This natural cosmogenic (cosmic-ray-formed) ^{14}C is then rapidly oxidized by OH^- (hydroxide ions), initially to form mostly molecules of ^{14}CO (carbon monoxide), and then these ^{14}CO molecules are rapidly oxidized to $^{14}CO_2$ (carbon dioxide). In these forms, ^{14}C is distributed throughout the Earth's atmosphere, first by jet stream stratospheric winds and then by slower, but more complete, mixing within tropospheric air masses. Even though ^{14}C production at the geomagnetic poles is about five times that at the geomagnetic equator, cosmic-ray-produced ^{14}C becomes generally well mixed by the time ^{14}C-tagged CO_2 molecules reach the planetary surface and become incorporated into various forms of biota or dissolved in water at the surface of the world's oceans.

Because oceans cover almost three-quarters of the Earth's surface, the largest percentage of ^{14}C is found in marine environments as dissolved inorganic carbonates (DIC) such as CO_2, or in the form of carbonates or bicarbonates. The majority of this marine ^{14}C is found in the deeper parts of the world's oceans. A very small percentage of the Earth's ^{14}C inventory becomes part of the terrestrial biosphere, first by being incorporated into plant biomass by means of several photosynthetic pathways, then into organisms that depend on plants for food, and then up the entire food chain. Thus all terrestrial living plant and animal communities that are, directly or indirectly, dependent on plants as a food resource are tagged with ^{14}C (Usoskin and Kromer, 2005).

While individual ^{14}C atoms will decay back into ^{14}N in living tissue, they are continually being replaced through the consumption of plant or animal biomass and the physiological processing of this biomass by various life forms. These metabolic processes in most *living* terrestrial organisms maintain the ^{14}C content in *approximate* equilibrium with atmospheric ^{14}C concentrations. However, once metabolic processes cease, for example, because of the death of a plant or animal, the amount of ^{14}C begins to decrease in that organism by negative beta (β^-) decay at a rate characterized by its half-life.

The half-life ($t_{1/2}$) of any radioactive isotope expresses the time interval during which that isotope will decrease by one-half (50 %). For every subsequent half-life interval, its concentration will decrease by a factor of 2 (another 50 %). In large part because of the very high energies involved in binding the atomic nucleus together, the decay rates of radioactive isotopes are highly stable and, with relatively rare exceptions (e.g., <1 % variations in electron-capture rates), cannot be altered by ordinary physical or chemical processes operating in any natural environment that now exists on our planet.

Since ^{14}C exhibits a half-life of ~5,700 years, the amount of ^{14}C contained in a carbon-containing sample will decrease by 50 % during every 5,700-year interval following its withdrawal from an active carbon reservoir at death, unless one or more contaminating processes cause carbon-containing compounds exhibiting different ^{14}C concentrations to be added to the sample matrix.

If all of the assumptions of the ^{14}C dating model are fulfilled for a given organic sample (see next section), a measurement of the residual ^{14}C concentration can be used to infer an accurate age for that sample. However, there are many factors that can impinge on the ^{14}C activity measured in a carbonaceous sample and, thus, affect the degree to which that ^{14}C concentration can be used directly to infer accurately and precisely the age of that sample.

Assumptions

The ^{14}C age of a given sample is inferred primarily based on a measurement of its residual ^{14}C content. To be able to infer an accurate age based on that measurement (at a useful level of precision), a set of major assumptions must hold within relatively narrow limits. These assumptions can be briefly summarized as follows (Taylor, 1987, 2001):

1. The concentration of ^{14}C in each carbon reservoir has remained constant at least over the last 100,000 years (i.e., temporally consistent levels of ^{14}C worldwide).
2. Complete and rapid mixing of ^{14}C throughout the various carbon reservoirs is achieved on a worldwide basis on a time scale of less than a few decades (i.e., relatively rapid achievement of global equilibrium in ^{14}C mixing).
3. Carbon isotope ratios in samples have not been altered except by ^{14}C decay since these sample materials ceased to be an active part of one of the carbon reservoirs (e.g., at the death of an organism when its metabolic or physiological processes stop).
4. The half-life of ^{14}C is accurately known to an appropriate level of precision.
5. Natural levels of ^{14}C can be accurately measured to appropriate levels of precision.

An additional requirement for optimal utilization of the ^{14}C method is that there is a firmly documented and explicit physical contextual relationship between a well-characterized organic sample whose ^{14}C concentration is to be measured and some specific event or phenomenon to be dated (i.e., a secure link exists between the dated sample and an archaeological layer needing an age determination). Field archaeologists, geologists, or historical specialists who collect and submit samples for ^{14}C measurement are generally responsible to insure that such contextual requirements are known and reliable.

Accuracy and precision

In this discussion, "accuracy" refers to the process of obtaining a valid or correct age – the true age as opposed to one that deviates by many years. In contrast, "precision" refers to the degree of uncertainty within which a given value is expressed – usually a plus and minus estimate indicating a range within which the age is likely to fall. In ^{14}C dating studies, a realistic overall level of accuracy and precision for a given sample depends on a consideration of additional factors. When all relevant data are evaluated critically, a review of these factors often results in decreasing significantly the overall *effective* accuracy and precision of a single ^{14}C value; it tends to increase the uncertainty term**.** The measurement of precision is typically based primarily on counting statistics, and it should be regarded as providing a way of defining a *minimum* dating precision associated with a single sample.

One cannot overemphasize the importance of keeping the entire range of relevant variables in mind if one wishes to evaluate any single ^{14}C age estimate, or suite of multiple estimates, to define the effective accuracy and precision of ^{14}C age determinations. Such a consideration highlights the value of duplicating ^{14}C determinations to increase the quality of ^{14}C evidence and therefore the validity of a chronometric temporal assignment for a given feature, stratigraphic level, artifact, or cultural context.

Conventions and definitions

A set of conventions, widely accepted in the ^{14}C research community, has defined and standardized how ^{14}C age determinations are expressed. There are three widely recognized ^{14}C age expressions: (1) conventional radiocarbon age, (2) reservoir-corrected radiocarbon age, and (3) calibrated radiocarbon age.

Conventional radiocarbon age

A conventional radiocarbon age assumes: (1) the use of 5,568 (~5,570) years as the ^{14}C half-life (the original "Libby half-life"), even though the actual value appears to lie closer to 5,700 years; (2) the use of an oxalic acid ($H_2C_2O_4$) preparation – a 1957 "old" (OXI) or 1977 "new" (OXII) oxalic acid – distributed by the US National Bureau of Standards (NBS) [now known as the National Institute of Standards and Technology (NIST)], or another standardized sample material with a known ^{14}C content serving as a secondary standard to define the "zero" ^{14}C age in the terrestrial biosphere; (3) the use of AD 1950 as the zero point from which to count ^{14}C time (i.e., AD 1950 = 0 BP on the ^{14}C time scale); (4) a normalization of ^{14}C activity in all samples to a common $\delta^{13}C$ (the isotopic signature represented by the ratio of ^{13}C to ^{12}C) value to account for isotope fractionation effects; and (5) an assumption that ^{14}C concentrations in living organisms in all reservoirs have remained constant over the ^{14}C time scale. The fifth proviso means that conventional ^{14}C values are *not calibrated* (Stuiver and Polach, 1977).

Primary citation of a conventional ^{14}C age determination must always be accompanied by a term that provides an estimate of the degree of analytical or measurement uncertainty. Since statistical constraints are usually the dominant and most easily quantifiable component of the analytical uncertainty of a ^{14}C age expression, this value is sometimes informally, but strictly speaking incorrectly, referred to as the statistical "error." It is more appropriately termed the *measurement uncertainty.* This "±" term is suffixed to all appropriately documented ^{14}C age estimates. It is typically expressed at the ±1 sigma (±1σ) level, which means one standard deviation above and below the calculated age.

There has been, and continues to be, some variability among laboratories as to the procedural conventions and mathematical protocols used in the calculation of the measurement uncertainty. For this and other reasons, various suggestions have been offered from time to time as to whether some multiplier factor should be applied to such values depending on the demonstrated experimental rigor of a given laboratory in its assignment of a given analytical uncertainty. This is one of the reasons that a laboratory number and an appropriate primary bibliographic reference should be associated with each ^{14}C age citation. Over several decades, the declining practice of laboratories publishing their primary "date lists" makes it even more important that such bibliographic reference information be included in some form when the values themselves or inferences based on them are published. When such information is available, it can facilitate an appropriate examination of the technical background of the measurement when questions are raised concerning its accuracy and/or precision.

For conventional ^{14}C ages, the current practice of the journal *Radiocarbon* is to publish conventional ^{14}C dates as defined above only as BP values. For example, using this terminology, the expression of "2,500 ± 50 BP" is equivalent to "2,500 ± 50 ^{14}C years before AD 1950 where ±50 indicates the measurement precision based on counting statistics expressed as a ±1 sigma range and with the ^{14}C age expression having been normalized to a $\delta^{13}C$ value of −25 ‰" (Stuiver and Polach, 1977; Long, 2000).

Reservoir-corrected radiocarbon age

For samples from some carbon reservoirs, conventional contemporary standards may not define a zero ^{14}C age. A reservoir-corrected radiocarbon age can sometimes be calculated by first documenting the amount of apparent age exhibited in ^{14}C dates determined on modern control samples and then correcting for the observed deviation in other dates on archaeological materials with the assumption that the age of the archaeological specimen and that of the control sample have been subjected to the same offsetting environmental effects. Reservoir corrections can range from less than 100 years to, in exceptional cases, many thousands of years.

The most intensive study of reservoir effects has been undertaken for marine organisms, specifically the carbonate component of marine shells. Reservoir corrections of ages obtained from marine shells currently employ regionally based numerical expressions which define the difference between the worldwide "average" age observed for marine organisms and that exhibited in a particular part of the marine reservoir from which a sample has been obtained. Unfortunately, not only are marine reservoir correction values geographically variable but, in addition, in some regions, these values also change significantly over time (e.g., Taylor et al., 2007). For some samples, especially those from certain nonmarine environments, it is difficult to obtain accurate and consistent reservoir corrections. For example, freshwater gastropods can exhibit great variability in their initial ^{14}C concentrations, reflecting in some cases annual seasonal variations in sources of carbonates in their environments as well as other factors.

Calibrated radiocarbon age

A calibrated radiocarbon age takes account of the fact that ^{14}C activity in living (or zero age) organisms *on a worldwide basis* has not remained constant over time. The offsets, or increases and decreases in ^{14}C abundance, are generally referred to as representing *secular variation* in the radiocarbon time scale (Suess, 1965). Because of these secular variation effects, one must distinguish between "^{14}C time" as defined by conventional ^{14}C ages and "real time" as expressed by a calendar, solar, or calibrated age. Secular variation has been viewed as exhibiting two major components: long-term or major trends and shorter-term higher frequency offsets. The shorter-term perturbations are often referred to as de Vries effects, named after the Dutch scientist, Hessel de Vries, who first focused attention on them (de Vries, 1958). The shorter-term perturbations are sometimes also referred to as "wiggles" or "warps" in the radiocarbon time scale.

As noted above, conventional ^{14}C ages are expressed with the notation BP (before [the] present) and defined in terms of several parameters. Calibrated ^{14}C values are typically expressed with the notation cal BP, cal BC, and/or cal AD. Some publications employ a terminology that includes or substitutes the expressions "CE" (Common or Current Era) for AD and "BCE" (Before [the] Common or Current Era) for BC.

The existence of ^{14}C secular variation reflects the fact that, contrary to the conventional assumption, the concentration of ^{14}C in each carbon reservoir has not been constant over geologically recent times. The long-term variations in ^{14}C concentrations have been largely traced to changes in the intensity of the dipole magnetic field of the earth while the short-term variations are associated with changes in components of the magnetic field of the sun together with various environmental parameters such as exchange rates among the carbon reservoirs

Because of these offsets, "radiocarbon years," as expressed by conventional ^{14}C ages, and "real years," as determined by solar or calendrical reckoning, are not of equal duration for most periods. Since varied terms for "real time" (e.g., solar, sidereal, calendar, or calibrated time) have tended to be used interchangeably, this discussion will use "calendar" or "calibrated" to designate it. Some have nevertheless argued that the term "solar" years would be more appropriate because, strictly speaking, there are (and have been) different types of calendars in use, not all of which have used solar years as the basis of recording the passage of time (Stuiver and Suess, 1966).

Calibrating ^{14}C values into calendar years was initially achieved by consulting tables or plots of the relationship between ^{14}C dates obtained from tree rings that were dated independently through dendrochronology (tree-ring dating). Such a comparison revealed for different periods the amount of offset between ^{14}C dates based on single tree rings or on 10 to 20 tree ring segments and the equivalent solar time based on dendrochronological determinations of the age of that wood sample. With increasing precision of the calibration datasets – initially for the Holocene and now increasingly for the terminal Pleistocene as well – together with the widespread availability of microcomputers and the Internet, a number of approaches using computers and web sites to enable the calibration process are now available.

Figure 2 is a plot of the offset (in years) between calendar (or calibrated) time and ^{14}C time for the period from 0 to 15,000 calendar years BP; the plot is based on the IntCal09 dataset (Reimer et al., 2009). The relationship between ^{14}C ages and calendar ages from 0 to 12,550 cal BP has been calibrated using dendrochronologically dated wood, while the interval from 12,550 to 15,000 years has been calibrated on the basis of paired uranium series/^{14}C dates on samples of corals and foraminifera from marine cores. The ages established from the dendrochronological or uranium-series determinations are plotted on the horizontal axis, while the difference in years between the known age and the ^{14}C age of the calibration samples is plotted on the vertical axis. The data points that are plotted below the "0" line (the period from about 500 to 2,000 BP) indicate conventional ^{14}C values are "too old" with reference to calendar time (meaning that during that period there was somewhat *less* ^{14}C in living materials as compared with ^{14}C contained in recent living materials on a worldwide basis), while the data plotted above the "0" line indicate conventional ^{14}C values are "too young" with reference to calendar time (meaning that during that period there was somewhat *more* ^{14}C in living materials as compared with ^{14}C contained in recent living materials on a worldwide basis). As an example, the data plotted in Figure 2 indicate that conventional ^{14}C age determinations are a little over 1,000 years "too young" at 10,000 cal BP.

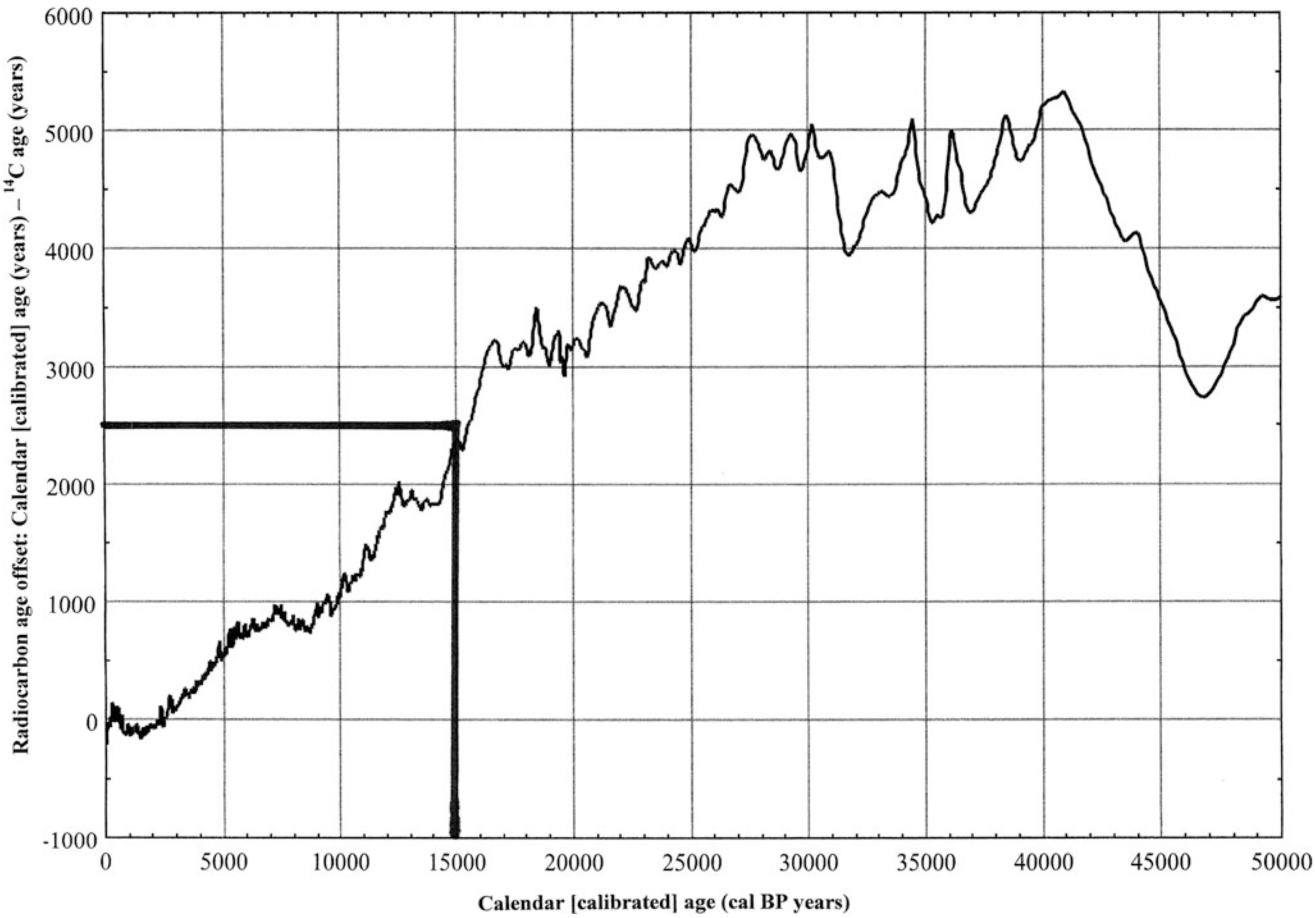
Radiocarbon Dating, Figure 2 Secular variation: major trends over the period 0–15,000 cal BP showing deviations (in years) between calendar/calibrated time and ^{14}C time. Offset values (on the vertical axis) are expressed in calendar/calibrated years based on the IntCal09 data set (Reimer et al., 2009) (Plot by J. R. Southon, University of California, Irvine).

Figure 3 plots the offset from 0 to 50,000 years using the same calibration data set as in Figure 2 (Reimer et al., 2009). The time period covered by Figure 2 is indicated by the rectangle in the lower left corner of Figure 3. As in Figure 2, those conventional ^{14}C values registering "too old" are plotted below the "0" line, and those registering "too young" are plotted above the "0" line. For example, Figure 3 indicates that a conventional ^{14}C age determination is about 4,000 years "too young" at 25,000 cal BP.

Figures 2 and 3 clearly illustrate the long-term trends in ^{14}C secular variation offsets. One can also note in both figures the shorter-term, rapidly changing "warps" in the radiocarbon time scale. The implications for calibration of ^{14}C values due to the magnitude of some of these short-term variations are illustrated in Figure 4. Calibration of the conventional ^{14}C value of 2,300 ± 15 BP is illustrated in Figure 4a, while calibration of 2,450 ± 15 BP is presented in Figure 4b. On the vertical axis of both parts of this figure, the ^{14}C ages of the two examples are plotted to show their $\pm 1\sigma$ (dark shaded area) and $\pm 2\sigma$ (dark and lighter shaded areas) ranges. The dark shaded irregular curves of varying width running approximately diagonally through these plots represent the relationship between the ^{14}C ages and the known ages of the series of samples used for ^{14}C calibration (Stuiver and Reimer, 1993).

Because of the variable or "accordion-like" characteristics of the plotted relationship between ^{14}C time and calendar time as illustrated in this mid-1st millennium BC period, the calibration of these two ^{14}C ages, which are only 150 years apart in ^{14}C years, reveals that the "real-time" equivalents of these two ^{14}C ages are significantly different. The calibration data associated with the 2,300 ± 15 BP ^{14}C-content-inferred age (Figure 4a) reflects a period when the contemporary ^{14}C activity in the atmosphere was undergoing rapid change as shown by the curve with a steep slope. This allows a much more precise resolution of the real-time equivalents of a given ^{14}C concentration measured in a sample. As plotted on the horizontal axis of Figure 4a, the $\pm 2\sigma$-based calibrated range for 2,300 ± 15 BP ranges over a 30-year spread from 400 BC to 370 BC.

In contrast, the calibration data associated with the ^{14}C age of 2,450 ± 15 BP falls on a lengthy plateau formed by



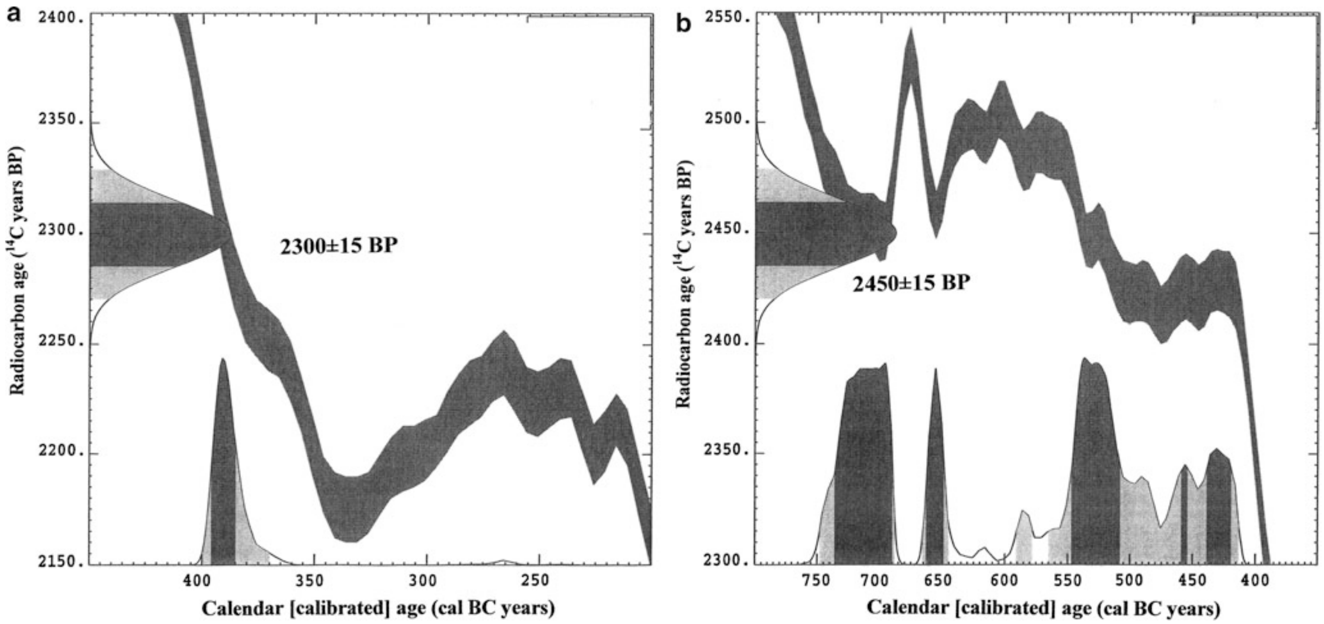
Radiocarbon Dating, Figure 3 Secular variation: major trends over the period 0–50,000 cal BP showing deviations (in years) between calendar/calibrated time and ^{14}C time. The rectangular area in lower left corner defined by heavy lines represents the coverage of the secular variationplot illustrated in Figure 2. Offset values (on the vertical axis) are expressed in calendar/calibrated years based on the IntCal09 data set (Reimer et al., 2009) (Plot by J. R. Southon, University of California, Irvine).

some complex "wiggles" in the ^{14}C time spectrum. In this case, the ^{14}C activity in calibration samples ranges over about a 350-year period. These data indicate that, during this period, the ^{14}C time scale is "warped" or significantly spread out, i.e., the ^{14}C content of samples, on a decade by decade and century by century basis, had not been changing as rapidly as it had only 150 years previously. In Figure 4b, the plotted ^{14}C value intercepts at multiple points and at varying levels of statistical significance, the calibration data over almost the entire 350-year time span of this plateau. Thus the calendar age equivalents of this particular ^{14}C value as expressed at various levels of statistical significance range over the 350-year spread from about 750 to 400 BC.

Defining the lower ^{14}C dating limit

The routine lower dating limit of the ^{14}C method is typically considered to be ~300 calendar years before present, which is equivalent to ~200 ^{14}C years. The physical basis of the lower limit is primarily the product of the interplay of three factors – one of which reflects natural short-term ^{14}C perturbations while the other two are caused by anthropogenic or human impacts. Any statement concerning a lower limit also must take into consideration the statistical precision associated with a given ^{14}C determination. For samples with uncertainty terms of >80 years, the lower ^{14}C dating limit may have to be extended beyond 300 calendar years by up to another century. In most cases, the interaction among these three physical factors together with statistical considerations associated with ^{14}C age measurements produces an ambiguous relationship between ^{14}C content and chronometric time for materials that were living during the last two centuries. Under certain rare circumstances, it is possible to assign a finite age younger than 300 calendar years.

The three major factors which generally limit the resolution of younger ages include: (1) recent natural short-term variations (de Vries effects) in atmospheric ^{14}C concentrations caused primarily by variations in several



Radiocarbon Dating, Figure 4 Secular variation: de Vries effects and their influence on dating precision. (**a**) Calibration of 2,300 ± 15 BP ^{14}C years yields a narrow range of uncertainty of about 30 years. (**b**) Calibration of 2,450 ± 15 BP ^{14}C years yields a wider range of uncertainty of about 350 years (Data from Reimer et al. (2009). Plot by CALIB 6.0; Stuiver and Reimer (1993)).

components of the solar magnetic field or solar wind; (2) the Fossil Fuel, Industrial, or Suess Effect which, beginning in the late eighteenth century, involved the introduction of ^{14}C-free CO_2 into the atmosphere as the result of the combustion of various types of fossil fuel carbon compounds, such as that contained in coal, and then later from petroleum-based products such as gasoline (Suess, 1955); and (3) the nuclear or Libby Effect which, beginning in the mid-1940s, initiated the production of artificial ^{14}C ("bomb ^{14}C") as a consequence primarily of neutrons produced during the detonation of thermonuclear weapon devices in the atmosphere in the early 1960s.

By the early 1950s, the effect of the Industrial/Suess Effect depressed the ^{14}C concentration in the atmosphere by almost 3 %. That process was reversed with the production of bomb ^{14}C which by 1963 had almost doubled the amount of ^{14}C in the atmosphere. These effects were significantly less in marine environments because of the much larger percentage of ^{14}C in the oceans, which moderated the rates of change. Atmospheric bomb ^{14}C levels peaked in 1963 because most atmospheric nuclear weapon testing was halted by the first international test ban treaty. This was followed by a slow decrease as this ^{14}C mixed into other carbon reservoirs.

In general, as a consequence of the complex interplay of these two anthropogenic factors combined with post-sixteenth-century natural ^{14}C perturbations, ^{14}C data cannot be employed to assign a specific age to materials dating to less than about two centuries except under special circumstances and usually with extended efforts. By convention, any sample exhibiting an age equivalency from 0 to 200 BP can be referred to as "modern," and any sample whose ^{14}C content exceeds that of the contemporary standard (i.e., contains bomb ^{14}C) may be referred to as ">modern," i.e., "greater than modern" (Stuiver and Polach, 1977).

Defining the upper ^{14}C dating limit

The current routine ^{14}C upper dating limit, expressed in terms of ^{14}C infinite ages, currently ranges between about >40,000 and >60,000 years depending largely on the characteristics of instrument configurations and computational protocols in different ^{14}C laboratories. Infinite ages, identified by the prefixed "greater than" (>) symbol, generally indicate that the ^{14}C concentration measured in a sample cannot be distinguished from the background values characteristic of a given counting system at some explicitly defined level of statistical significance**.** Background count rates, or $^{14}C/^{12}C$ ratios, are obtained from samples of sufficient geological age that it can be reasonably inferred that they no longer contain measurable amounts of cosmic-ray-produced ^{14}C.

The specific values of the counting background are unique to every instrument system. The maximum infinite ^{14}C ages expressed are a function of the characteristics of a given counting system, which include factors such as the magnitude and stability of the backgrounds, the ratio between that value and the value associated with contemporary ^{14}C reference standards, and the statistical protocols employed in a given laboratory.

The principal *physical* basis of this upper age limit is a function of the decay rate of ^{14}C which, after 8–10 ^{14}C half-lives, reduces ^{14}C concentrations in natural samples below the effective detection levels that are currently routinely possible, whether one uses conventional decay (beta) counting or direct (ion) counting by accelerator mass spectrometry (AMS) technology. An additional factor is the significant challenge of removing modern or significantly younger contamination during the preparation of samples with infinite ages in excess of 40,000–50,000 years.

An extension of the upper dating limit to ~75,000 years has been achieved in several decay counting laboratories on a relatively small number of samples by the combined use of isotopic enrichment and very low and stable background decay counting instrumentation. Isotopic enrichment is accomplished by artificially increasing the concentration of ^{14}C in a sample and monitoring the amount of that enrichment by measuring $\delta^{13}C$ values in the sample. The counting characteristics in these facilities were made possible in most cases by employing special experimental arrangements, such as counting instrumentation located 10–30 m underground to minimize background levels. With regard to the upper dating limit for facilities employing AMS technology, one laboratory reported the equivalent of a 60,000-year measurement on a sample of wood from the Pliocene epoch (5.3–2.5 Ma ago), and another facility obtained the equivalent of an 80,000-year measurement on a special background blank (diamond) as a means of monitoring operating characteristics of an instrument component (Kirner et al., 1997; Taylor and Southon, 2007). However, the *routine* extension of the effective ^{14}C time scale beyond 50,000 years using AMS technology will largely depend on future research that includes the ability, on a long-term consistent and reproducible basis, to minimize carbon microcontamination introduced during the various stages of sample preparation.

Because of misunderstandings of the nature of low-level counting technology terminology employed in some popular treatments, it is probably helpful to emphasize that the >60,000- or >80,000-year figures cited here as examples are *infinite age expressions*. These figures simply indicate the maximum age equivalent that can be inferred from counting data exhibited in a particular instrument using standard statistical protocols for a specific sample. All that can be meaningfully deduced from such expressions is that the ages quoted indicate that the sample ages are *in excess by an unknown amount of the value cited*. The amount of time involved can literally range from a few hundred to many hundreds of millions of years.

Prominent geological and archaeological applications

Of the estimated 500,000 ^{14}C age determinations processed since 1946, some suites of ^{14}C measurements have been applied to topics that elicited special attention from archaeologists and Quaternary geologists. A few of the most prominent scientific applications are briefly noted below.

Two Creeks fossil forest (Wisconsin): Pleistocene/Holocene boundary

For geologists, one of the principal terrestrial characteristics of the Pleistocene epoch was the multiple waxings and wanings of large continental glaciers in North America and northwestern Europe. In the late nineteenth and early twentieth centuries, four major glacial and four major interglacial stages were identified based on the sequence of sediments (glacial moraines) associated with the maximum extent of the glacial advances that were identified in the European Alps. One question raised was whether the most recent of these major glacial periods in Europe, called the Würm, was coincident in time with the last major glacial phase identified in North America, called the Wisconsin.

A number of localities contain geological evidence of events associated with the terminal Wisconsin, and many have been examined. In some of these sites, sediments associated with the retreat of the ice mass, followed by a temporary advance, and then a final retreat have been documented. This series of events has been studied in great detail in sediments located in and around Two Creeks, Wisconsin, a locality on the western shore of Lake Michigan. On land abandoned by the retreating North American Laurentide Ice Sheet, a forest developed. This forest was then subsequently overrun as the glacier temporarily moved south again during the brief colder event called the Valders ice advance. The final retreat of the ice followed thereafter. The geological evidence of this glacial retreat-advance-retreat interval is the Two Creeks fossil forest.

In the pre-^{14}C period, the Two Creeks interval had been dated between 24,000 and 19,000 years ago based in part on the correlation of North America varve sequences with those in Scandinavia. In an early group of ^{14}C dates run by Libby, seven samples of wood and peat collected from the Two Creeks forest bed and from two nearby sites exhibiting the same stratigraphy were dated. The resultant ^{14}C ages ranged from 10,877 ± 740 BP to 12,168 ± 1,500 BP and were averaged for a composite age of 11,404 ± 350 BP (Libby, 1952, 88). By 1963, 14 additional ^{14}C measurements on wood or peat from Two Creeks and adjacent localities had been obtained by four other laboratories. Two of these dates were clearly aberrant. The remaining 12 measurements spanned 10,400 ± 600 BP to 12,200 ± 400 BP. The average of the 19 acceptable measurements obtained up to that date was 11,350 BP. If only measurements associated with statistical errors of less than 500 years obtained by newer technologies were averaged, the value was 11,600 BP (Broecker and Farrand, 1963).

Additional ^{14}C measurements on samples collected from the Two Creeks locality in the 1990s yielded a range of dates from 11,640 ± 160 BP to 11,800 ± 160 BP which, when the error terms in the measurements were considered, essentially confirmed the earlier suite of measurements. Cross dating tree rings from a series of tree segments recovered from Two Creeks sediments indicated that forest growth in this area occurred over a period between 200 and 300 years (Leavitt and Kahn, 1992).

Tule Springs, Nevada: Clovis or pre-Clovis?

In the early 1960s, the decision to undertake large-scale excavations at Tule Springs, Nevada, was stimulated in large part by a single ^{14}C determination of >23,000 years obtained by Libby's Chicago group (Libby, 1952, 121). The sample analyzed was characterized as "charcoal" recovered from what had been labeled a "hearth-like feature" by earlier excavators at the site, who associated it with sediments containing the bones of extinct fauna. The significance of this date from the site was that it suggested an antiquity for the initial peopling of the New World significantly earlier than was realized in the 1950s. By that time, the earliest well-documented hunters and gatherers in North America were those associated with a distinctive fluted projectile point known as Clovis and commonly found in mammoth kills, followed by groups who made the distinctive Folsom point associated with late Pleistocene bison (Sellards, 1952). Subsequent radiocarbon dating by Libby (1955) and others suggested that Clovis and Folsom occupations dated around 10,000 ^{14}C years BP. The date in excess of 23,000 BP from Tule Springs was obviously of considerable interest to many New World archaeologists.

Prompted by the very early ^{14}C determination, extensive excavations were carried out at Tule Springs in the early 1960s. This work represented one of the first examples in New World archaeology of a research design that included recovery of a large suite of ^{14}C samples during the excavation campaign, and a total of 59 ^{14}C determinations were obtained from Tule Springs and associated sites.

After the 1960s excavations, the only uncontested artifacts recovered at Tule Springs were associated with sediments dating in the 10,000–11,000 BP range. No artifacts were associated with earlier sediments. More significantly, the features originally identified as "hearths" containing "charcoal" were determined to be concentrations of decayed plant remains associated with water channel debris or spring deposits.

The results of the research at Tule Springs led to the site's removal from the category of potential pre-Clovis localities. More broadly, the Tule Springs project demonstrated the need for an on-site geoarchaeologist (in this case it was C. Vance Haynes, Jr.) to document the stratigraphic context of ^{14}C samples in the field, to evaluate their origins, and to interpret the resulting dates (Haynes et al., 1966).

Monte Verde (Chile): pre-Clovis in South America?

Beginning in 1976, excavations at Monte Verde, a site located in the Lakes region of south-central Chile, recovered a wide-ranging cultural assemblage of wood, stone, fiber, and bone materials in seemingly well-defined, multicomponent, stratigraphic contexts with associated wood and charcoal samples. During the course of a decade, 35 ^{14}C determinations were obtained from several kinds of samples from this site. The earliest ^{14}C dates reported as being clearly associated with artifacts and other cultural materials ranged from 12,230 ± 140 to 12,780 ± 240 years BP (Dillehay, 1989, 1997; Dillehay et al., 2008).

If these ^{14}C values from Monte Verde are, on the whole, accepted as valid, it would indicate that the lithic artifact inventory from Monte Verde, which appears to have no developmental relationship to the Clovis assemblages of North America, was present on the coast of South America ten centuries prior to Clovis. Acceptance of the validity of this conclusion renewed discussions about how humans could arrive in South America so early, i.e., which routes were taken by early human populations as they moved south from presumed entry points in eastern Beringia into the New World. If humans were indeed present on the coast of Chile a millennium prior to Clovis, then a migration route might reasonably be sought along Pacific coastal zones and not through the narrow ice-free corridor between the Laurentide and Cordilleran ice sheets in the northwestern interior of North America. Unfortunately, many of the sites where evidence of a coastal route might be found are submerged beneath as much as ~100 m (~300 ft) of the ocean as a consequence of the terminal Pleistocene-early Holocene rise in sea level inundating the coastal plains.

Naturally with such an important and controversial site, considerable discussion arose about the integrity of the artifact assemblage, including the quality of the associations claimed with ^{14}C values at all levels in the site. Potential problems with the validity of ^{14}C values from Monte Verde have been addressed in several studies (e.g., Taylor et al., 1999). The excavators argued that there was no reasonable basis on which to suspect major sample contamination given the range in materials that were sampled, the overall consistency in the values obtained, and the character of the sediments from which the samples were recovered. However, attention had been called to a significant ^{14}C dating anomaly centered on a single sample from Monte Verde. Two segments of the same mastodon bone yielded ^{14}C ages of 6,550 ± 160 BP and 11,990 ± 200 BP. A redating of both of these segments using molecular fractions (total amino acids and ultrafiltered gelatin) isolated from both segments yielded a set of four ^{14}C values ranging from 12,455 ± 40 BP to 12,510 ± 60 BP. In this way, the younger ^{14}C age assigned to one of the mastodon bone segments was demonstrated to be clearly erroneous (George et al., 2005).

Others have pointed to the possibility of major marine and/or terrestrial reservoir effects on samples from the vicinity of the site. The basis for this inference is that there are several active and extinct volcanoes situated along a north/south axis at the western base of the Cordillera de Los Andes. However, all of them are situated to the east and thus leeward of Monte Verde with the closest located ~65 km southeast of the site. Because the current prevailing winds consistently blow from the coastal zone located ~45 km to the west of the site, volcanic emissions from known volcanoes would not be expected to reach the region around Monte Verde. Even if wind patterns in the late Pleistocene were such that trace amounts of CO_2 laden magmatic gas (which would be "dead" with respect to ^{14}C content) might be present, attenuation factors would be significant, and any postulated effect would be expected to produce, at most, an offset of a few hundred years, unless a heretofore unknown magmatic vent existed closer than a few tens of meters from the site. Although questions remain and studies continue (e.g., Dickinson, 2011), there is currently no evidence of major anomalies which could significantly affect the validity of the Monte Verde ^{14}C values.

The Kennewick human: the most complete early Holocene Paleoamerican skeleton

In 1996, first a skull and then, over a period of several months, a substantial number of postcranial bones were recovered from a lake created by a dam in the Columbia River near the community of Kennewick in the state of Washington. This skeleton, found in shallow water sediments adjacent to a collapsing embankment, exhibited morphological features which, to some biological anthropologists, appeared to be distinct from those exhibited by contemporary Native American populations. The initial suggestion was that it represented an early Euro-American settler, but it was then observed that the bones exhibited several morphological characteristics indicating a possible connection to several ancient Southeast Asian populations (Chatters, 2001). Multiple ^{14}C determinations established the age of the Kennewick skeleton as being early Holocene in date – in excess of 7,000 BP (Taylor et al., 2001). The implications of these two apparent facts – an early Holocene age and a distinct anatomical morphology – for understanding the processes involved in the peopling of the Western Hemisphere from Asia continue to be debated.

One immediate question raised by the Kennewick skeleton is whether one or more early Holocene New World hunter and gatherer groups may have at some point in the Holocene become extinct, thus leaving no living Native American descendants. This possibility has prompted the development of a distinction between Paleoamerican, i.e., early New World populations which may have no modern descendants, and Paleoindian, i.e., early New World populations having modern Native American descendants.

Ötzi, the Iceman: European Chalcolithic mummy

Radiocarbon determinations were employed to assign an age to mummified human remains discovered in 1991 within an ice field on a mountain pass in the Ötztal Alps on the Italian side of the border with Austria. Results of ^{14}C measurements on the corpse, clothes, gear, and associated plant remains, including mosses, of Ötzi, the iceman, indicated that he had died about 5,300 years ago, placing his lifetime within the European Chalcolithic or Copper Age (Prinoth-Fornwagner and Niklaus, 1994; Dickson et al., 2003, 2005).

The mummy has received widespread publicity as well as extensive scientific studies in an attempt to determine where the individual had lived, his dietary habits, and cause of death. He appears to have died from blood loss due to an arrow wound; thus he met a violent end. A recent examination of the distribution of the artifact materials associated with the body has led to the suggestion that the original context of Ötzi had been a "ceremonial burial" along with grave goods, the contents of which had been later dispersed when the grave environment thawed, and the body and its contents slumped downwards into a rocky hollow that preserved it from deterioration through exposure and destruction by glacial ice that covered the location (Vanzetti et al., 2010). This interpretation has been rebutted by Zink et al. (2011).

The Shroud of Turin

Probably the most widely known example of the use of ^{14}C to determine the true age of an important cultural object was its application to the Shroud of Turin, a piece of linen that many Christian adherents believe had captured the real image of Jesus of Nazareth when he was wrapped in it after his crucifixion. The question was whether the object dated from the first century CE when the execution occurred or the later part of the fourteenth century CE when the shroud was first noted in the historical record. Results of dating of the Shroud of Turin by three AMS ^{14}C laboratories determined that the flax from which the linen had been woven was growing at some point between the late thirteenth and the late fourteenth centuries CE (Damon et al., 1989). Thus, the Shroud of Turin was determined to be, in fact, a European medieval artifact. Concerns have been voiced by some that repairs or contaminations to the cloth may have skewed its dating, making it appear more recent than Roman in age, but such criticisms have been addressed, and the medieval date is considered reliable among dating specialists (Freer-Waters and Jull, 2010).

Summary

The "radiocarbon revolution" (Renfrew, 1973) initiated more than six decades ago by Willard Libby and his research collaborators actively continues, with ^{14}C typically playing a central role as the court of final appeal for archaeological chronology. Radiocarbon data often serve as the prime arbiter in resolving uncertainties and controversies about the chronological ordering of cultural materials, including in some cases historical period artifacts of problematic authenticity as well as human skeletal remains of disputed age.

For archaeologists and geologists, the most immediate and obvious impact of the ^{14}C method on the conduct of archaeological research has been the availability of a fixed-rate temporal scale of worldwide applicability for the late Quaternary. In providing a common frame of temporal reference for the late Pleistocene and Holocene, ^{14}C data has made possible a prehistory of the world by providing a time scale that transcends local, regional, and continental boundaries. As Grahame Clark (1970, 38) noted, radiocarbon "has contributed more than any other single factor to complete the world coverage of prehistoric archaeology, not to mention the way it has helped scholars to synchronize phenomena in different parts of the world." Without the time scale provided by ^{14}C data, prehistorians would still be, in the words of the late J. Desmond Clark, "foundering in a sea of imprecisions sometimes bred of inspired guesswork but more often of imaginative speculation" (Clark, 1979: 7).

For archaeologists, a less immediately recognized contribution of ^{14}C data has been the fact that ^{14}C-based age estimates provide a means of deriving chronological relationships totally independent of assumptions about cultural processes and completely unrelated to any type of manipulation of artifacts. When pressure to derive chronology primarily from the analyses of artifact data was reduced, inferences about the evolution of human behavior based on variations in environmental, ecological, or technological factors could be aggressively pursued employing an independent chronological framework (Bronk Ramsey, 2008).

The great technical success of the ^{14}C method also encouraged a major impetus for interdisciplinary research. It represented one of the major catalysts that moved both geologists and archaeologists increasingly to direct their attention toward analytical and statistical approaches in the manipulation and evaluation of data, as well as to maintain long-term collaborative relationships with colleagues in other scientific disciplines. It was therefore entirely understandable that an early proponent of interdisciplinary studies in archaeology, Frederick Johnson, also became an early advocate of the ^{14}C method among his colleagues. The general theme of his concerns at the inception of the method is still relevant as we observe the continuously expanding horizons of ^{14}C application in archaeological and geoarchaeological studies: "[P]rogress in the development of . . . [radiocarbon dating] depends to a large degree upon the character of the collaboration [between archaeologists and other scientists]. The laboratory procedure involves theories in physics and chemistry which for the most part are outside the experience of almost everyone who has a sample to be dated. On the other hand, the results secured are of little consequence unless they are directly or indirectly related to some stratigraphic sequence. The value of the laboratory results is enhanced by critical evaluation by other scientists. Most particularly, the reverse is true. This involves continual examination of all basic theory and hypotheses by everyone concerned. The future value and usefulness of the method depends in large measure upon the success of continued collaboration between physicists, archaeologists, geologists, botanists, and others" (Johnson et al., 1951, 62).

This injunction assumed an even greater significance with the introduction of accelerator mass spectrometry (AMS) technology for ^{14}C measurements. AMS methods permit analyses to be conducted on microgram amounts of organics and open up the possibility of extending the ^{14}C dating range. For archaeologists and Quaternary geologists, the utilization of submilligram-size samples will require even more rigorous attention to the evaluation of geological, geochemical, and archaeological contexts of samples. The need for interdisciplinary cooperation and collaboration will become even more critical as AMS technology assumes an ever increasing role in the ^{14}C measurements of archaeological and other late Quaternary paleoenvironmental and paleoecological materials.

Acknowledgments

The preparation of this article was, in part, supported by the Gabrielle O. Vierra Memorial Fund.

Bibliography

Arnold, J. R., 1981. Willard F. Libby (1908–1980). In *The American Philosophical Society Yearbook 1980*. Philadelphia: The American Philosophical Society, pp. 608–612.

Arnold, J. R., and Libby, W. F., 1949. Age determinations by radiocarbon content: checks with samples of known age. *Science*, **110**(2869), 678–680.

Broecker, W. S., and Farrand, W. B., 1963. Radiocarbon age of the Two Creeks Forest Bed, Wisconsin. *Geological Society of America Bulletin*, **74**(6), 795–802.

Bronk Ramsey, C., 2008. Radiocarbon dating: revolutions in understanding. *Archaeometry*, **50**(2), 249–275.

Calcagnile, L., D'Onofrio, A., Fedi, M., Mandò, P. A., Quarta, G., Terrasi, F., and Tuniz, C., 2010. Accelerator mass spectrometry. In *Proceedings of the 11th International Conference on Accelerators Mass Spectrometry (AMS-11), Rome, September 14–19, 2008. Nuclear Instruments and Methods Section B: Beam Interactions with Materials and Atoms*, B268(7–8), 693–1359.

Chatters, J. C., 2001. *Ancient Encounters: Kennewick Man and the First Americans*. New York: Simon & Schuster.

Chen, J., Guo, Z., Liu, K., and Zhou, L., 2011. Development of accelerator mass spectrometry and its applications. *Reviews of Accelerator Science and Technology*, **4**(1), 117–145.

Clark, G., 1970. *Aspects of Prehistory*. Berkeley: University of California Press.

Clark, J. D., 1979. Radiocarbon dating and African archaeology. In Berger, R., and Suess, H. E. (eds.), *Radiocarbon Dating: Proceedings of the Ninth International Conference, Los Angeles and La Jolla, 1976*. Berkeley: University of California Press, pp. 7–31.

Cook, G. T., Scott, E. M., and Harkness, D. D., 2010. Radiocarbon as a tracer in the global carbon cycle. In Froehlich, K. F. O. (ed.), *Environmental Radionuclides: Tracers and Timers of Terrestrial Processes*. Amsterdam: Elsevier. Radioactivity in the Environment 16, pp. 89–137.

Damon, P. E., Donahue, D. J., Gore, B. H., Hatheway, A. L., Jull, A. J. T., Linick, T. W., Sercel, P. J., Toolin, L. J., Bronk, C. R., Hall, E. T., Hedges, R. E. M., Housley, R., Law, I. A., Perry, C., Bonani, G., Trumbore, S., Woelfli, W., Ambers, J. C., Bowman, S. G. E., Leese, M. N., and Tite, M. S., 1989. Radiocarbon dating of the Shroud of Turin. *Nature*, **337**(6208), 611–615.

De Vries, H., 1958. Variations in concentration of radiocarbon with time and location on Earth. *Proceedings of the Koninklijke Nederlandse Akademie van Wetenschappen Series B*, **61**(2), 94–102.

Dickinson, W. R., 2011. Geological perspectives on the Monte Verde archeological site in Chile and pre-Clovis coastal migration in the Americas. *Quaternary Research*, **76**(2), 201–210.

Dickson, J. H., Oeggl, K., and Handley, L. L., 2003. The ice man reconsidered. *Scientific American*, **288**(5), 70–79.

Dickson, J. H., Oeggl, K., and Handley, L. L., 2005. The iceman reconsidered. *Scientific American, Special Archaeology Volume*, **15**(1), 4–13.

Dillehay, T. D., 1989. *Monte Verde: A Late Pleistocene Settlement in Chile. volume 1. Paleo-environment and Site Context*. Washington, DC: Smithsonian Institution Press.

Dillehay, T. D., 1997. *Monte Verde: A Late Pleistocene Settlement in Chile. volume 2. The Archaeological Context and Interpretation*. Washington, DC: Smithsonian Institution Press.

Dillehay, T. D., Ramírez, C., Pino, M., Collins, M. B., Rossen, J., and Pino-Nararro, J. D., 2008. Monte Verde: seaweed, food, medicine, and the peopling of South America. *Science*, **320**(5877), 784–786.

Freer-Waters, R. A., and Jull, A. J. T., 2010. Investigating a dated piece of the Shroud of Turin. *Radiocarbon*, **52**(4), 1521–1527.

George, D., Southon J. R., Taylor, R. E. 2005. Resolving an anomalous radiocarbon determination on Mastodon bone from Monte Verde, Chile. *American Antiquity*, **70**(4):764–770.

Haynes, C. V., Jr., Doberenz, A. R., and Allen, J. A., 1966. Geological and geochemical evidence concerning the antiquity of bone tools from Tule Springs, Site 2, Clark County, Nevada. *American Antiquity*, **31**(4), 517–521.

Johnson, F., Rainey, F., Collier, D., and Flint, R. F., 1951. Radiocarbon dating, a summary. In Johnson, F. (ed.), *Radiocarbon Dating: A Report on the Program to Aid in the Development of the Method of Dating*. Salt Lake City: Society for American Archaeology. Memoirs of the Society for American Archaeology 8, pp. 59–63.

Kirner, D. L., Burky, R., Taylor, R. E., and Southon, J. R., 1997. Radiocarbon dating organic residues at the microgram level. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, **B123** (1–4), 214–217.

Knezovich, J., Brown T., Buchholz, B., Finkel, R., Guilderson, T., Kashgarian, M., Nimz, G., Ognibene, T., Turney, S., and Vogel, J. (eds.), 2007. Accelerator mass spectrometry. In *Proceedings of the Tenth International Conference on Accelerator Mass Spectrometry, Berkeley, California, USA, 5–10 September 2005. Nuclear Instruments and Methods in Physics Research, Section B: Beam Interactions with Materials and Atoms*, **B259**(1), 1–816.

L'Annunziata, M. F., 2007. *Radioactivity: Introduction and History.* Amsterdam: Elsevier.

Leavitt, S. W., and Kahn, R. M., 1992. A new tree-ring width, $\delta^{13}C$ and ^{14}C investigation of the Two Creeks site. *Radiocarbon*, **34**(3), 792–797.

Libby, W. F., 1952. *Radiocarbon Dating*. Chicago: University of Chicago Press.

Libby, W. F., 1955. *Radiocarbon Dating*, 2nd edn. Chicago: University of Chicago Press.

Libby, W. F., Anderson, E. C., and Arnold, J. R., 1949. Age determination by radiocarbon content: world-wide assay of natural radiocarbon. *Science*, **109**(2827), 227–228.

Long, A., 2000. Radiocarbon: brief history of a journal. *Radiocarbon*, **42**(1), xvii–xx.

Pollard, A. M., 2009. Measuring the passage of time: achievements and challenges in archaeological dating. In Cunliffe, B. W., Gosden, C., and Joyce, R. A. (eds.), *The Oxford Handbook of Archaeology.* Oxford: Oxford University Press, pp. 145–168.

Prinoth-Fornwagner, R., and Niklaus, T. R., 1994. The man in the ice: results from radiocarbon dating. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, **B92**(1–4), 282–290.

Reimer, P. J., Baillie, M. G. L., Bard, E., Bayliss, A., Beck, J. W., Blackwell, P. G., Bronk Ramsey, C., Buck, C. E., Burr, G. S., Edwards, R. L., Friedrich, M., Grootes, P. M., Guilderson, T. P., Hajdas, I., Heaton, T. J., Hogg, A. G., Hughen, K. A., Kaiser, K. F., Kromer, B., McCormac, F. G., Manning, S. W., Reimer, R. W., Richards, D. A., Southon, J. R., Talamo, S., Turney, C. S. M., van der Plicht, J., and Weyhenmeyer, C. E., 2009. IntCal09 and Marine09 radiocarbon age calibration curves, 0–50,000 years cal BP. *Radiocarbon*, **51**(4), 1111–1150.

Renfrew, C., 1973. *Before Civilization: The Radiocarbon Revolution and Prehistoric Europe*. New York: Knopf.

Sellards, E. H., 1952. *Early Man in America*. Austin: University of Texas Press.

Stuiver, M., and Polach, H. A., 1977. Discussion: reporting of ^{14}C data. *Radiocarbon*, **19**(3), 355–363.

Stuiver, M., and Reimer, P. J., 1993. Extended ^{14}C database and revised CALIB 3.0 ^{14}C age calibration program. *Radiocarbon*, **35**(1), 215–230.

Stuiver, M., and Suess, H. E., 1966. On the relationship between radiocarbon dates and true sample ages. *Radiocarbon*, **8**(1), 534–540.

Suess, H. E., 1955. Radiocarbon concentration in modern wood. *Science*, **122**(3166), 415–417.

Suess, H. E., 1965. Secular variations of the cosmic-ray-produced carbon 14 in the atmosphere and their interpretations. *Journal of Geophysical Research*, **70**(23), 5937–5952.

Taylor, R. E., 1987. *Radiocarbon Dating: An Archaeological Perspective*. Orlando: Academic.

Taylor, R. E., 1996. Radiocarbon dating: the continuing revolution. *Evolutionary Anthropology*, **4**(5), 169–181.

Taylor, R. E., 2001. Radiocarbon dating. In Brothwell, D. R., and Pollard, A. M. (eds.), *Handbook of Archaeological Sciences*. Chichester: Wiley, pp. 23–34.

Taylor, R. E., and Southon, J. R., 2007. Use of natural diamonds to monitor ^{14}C AMS instrument backgrounds. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, **B259**(1), 282–287.

Taylor, R. E., Haynes, C. V., Jr., Kirner, D. L., and Southon, J. R., 1999. Radiocarbon analyses of modern organics at Monte Verde, Chile: no evidence for a local reservoir effect. *American Antiquity*, **64**(3), 455–460.

Taylor, R. E., Smith, D. G., and Southon, J. R., 2001. The Kennewick skeleton: chronological and biomolecular contexts. *Radiocarbon*, **43**(2B), 965–976.

Taylor, R. E., Southon, J. R., and Des Lauriers, M. R., 2007. Holocene marine reservoir time series ΔR values from Cedros Island, Baja California. *Radiocarbon*, **49**(2), 899–904.

Trumbore, S. E., 2000. Radiocarbon geochronology. In Noller, J. S., Sowers, J. M., and Lettis, W. R. (eds.), *Quaternary Geochronology: Methods and Applications*. Washington, DC: American Geophysical Union, pp. 41–60.

Usoskin, I. G., and Kromer, B., 2005. Reconstruction of the ^{14}C production rate from measured relative abundance. *Radiocarbon*, **47**(1), 31–37.

Vanzetti, A., Vidale, M., Gallinaro, M., Frayer, D. W., and Bondioli, L., 2010. The iceman as a burial. *Antiquity*, **84**(325), 681–692.

Zink, A., Graefen, A., Oeggl, K., Dickson, J., Leitner, W., Kaufmann, G., Fleckinger, A., Gostner, P., and Egarter-Vigl, E., 2011. The iceman is not a burial: reply to Vanzetti et al. 2011. *Antiquity*, **85**, 328.

Cross-references

Amino Acid Racemization
Chronostratigraphy
Climatostratigraphy
Dendrochronology
Geophysics
Great Plains Geoarchaeology
Kennewick Man
Monte Verde
Ötzi, the Tyrolean Iceman
Pre-Clovis Geoarchaeology
Stable Carbon Isotopes in Soils
U-Series Dating

RAMAN

Francesco Berna
Department of Archaeology, Simon Fraser University, Burnaby, BC, Canada

Synonyms

FT-Raman; Raman microscopy; Raman spectroscopy

Definition

Raman spectroscopy is a technique used to identify and characterize organic and inorganic compounds, and it has been used in the examination of materials possessing archaeological significance (Smith and Clark, 2004; Vandenabeele et al., 2007). It relies on inelastic scattering (i.e., Raman scattering) of monochromatic electromagnetic radiation, typically a laser, interacting with molecular vibrations in a sample. Specifically, photons of incident light strike the surface of a target specimen, and most of the photons are absorbed, reflected, or transmitted by the target material. A small part of the photon beam interacts with the specimen by deforming the atomic charge and inducing an instantaneous dipole moment in the molecule under investigation. Molecules affected in this way are excited to a higher energy state that is unstable and decays immediately; the decay process occurs mostly by elastic scattering (known as Rayleigh scattering) in which the molecules emit photons of equal energy and return directly to their original ground state of vibration. A small percentage of the photon emission is inelastic and leads to Raman scattering, which means that energy is emitted at levels both higher than and lower than that of the elastic Rayleigh scattering, i.e., the incident photon energy is not conserved. The frequency shift corresponding to the energy difference (positive or negative) between the incident and inelastically scattered photons is termed the Raman shift, and it is this aspect that informs about the target material by revealing spectra that are determined by its atomic and molecular composition.

Raman spectra can be plotted by graphing the energy differences between incident and Raman scattered photons against wave number/cm^{-1} (number of waves per cm). If the deformation of the electron charge caused by incident photons corresponds to a vibrational state of the molecule, the mode is Raman active, and a Raman scattering peak will be observed. The shape of a resultant curve with its peaks is typical of both elemental and structural features of the specimen and can be used for accurate identification and characterization of the compounds analyzed.

In modern Raman spectrometers, lasers are used as the incident light source. This source is necessary, as the Raman effect is weak, typically ~10^5 times weaker than the elastic component (i.e., Rayleigh scattering). Light beams with high monochromatic nature and flux are needed for satisfactory generation. Commonly, Raman spectrometers are coupled to an optical microscope to focus the laser beam onto a spot that can be as small as 1 μm in diameter. Raman-shifted radiation is then detected with a charge-coupled device (CCD) detector, and a computer is used for data acuisition and curve fitting. Modern Raman spectrometers are based on interferometer systems and Fourier transform-based signal treatment to improve the quality of the measured spectra (FT-Raman). In Raman spectroscopy, the main experimental variables are the laser wavelength, laser power, and time of excitation. The most commonly used lasers have the following frequencies: 514.5 nm (Ar+), 632.8 nm (HeNe), 647.1 nm (Kr+), 780 nm (diode), and 1,064 nm (Nd:YAG).

Raman spectroscopy probes molecular bond vibrations and therefore is sensitive to the composition, chemical environment, and crystal structure of the material sampled. It is thus an exceptional complementary method to FTIR for fingerprinting and unambiguously identifying crystalline or amorphous materials in any physical form, in both laboratory and in situ field locations. Appropriate experimental conditions are needed to avoid sample alteration during laser excitation and to suppress the fluorescence of naturally fluorescent organic materials – the atomic fluorescence of all organic and some inorganic materials – and fluorophores that have become incorporated into artifacts from handling, burial, or other processes. Raman spectroscopy is used to analyze a variety of materials, though it turns out to be particularly suitable for the analysis of metal oxides and pigments. Extensive Raman spectral libraries are openly available from numerous institutions (Vandenabeele et al., 2007).

Raman spectroscopy has also often been applied as a powerful analytical technique in mineralogy and gemology. The technique is particularly useful for the study of mineral inclusions, and from these examinations conclusions can be drawn about the geological genesis of the minerals and their provenience. Raman spectroscopy is also used for the analysis of rock art and tomb paintings, ceramics and glazes, glass and faience, lithics, metals, textiles and plant fibers, resins, waxes, organic residues, and biomaterials such as hair, skin, bone, and ivory (Smith and Clark, 2004).

Bibliography

Smith, G. D., and Clark, R. J. H., 2004. Raman microscopy in archaeological science. *Journal of Archaeological Science*, **31**(8), 1137–1160.
Vandenabeele, P., Edwards, H. G. M., and Moens, L., 2007. A decade of Raman spectroscopy in art and archaeology. *Chemical Reviews*, **107**(3), 675–686.

Cross-references

Fourier Transform Infrared Spectroscopy (FTIR)

REMOTE SENSING IN ARCHAEOLOGY

Stefano Campana
Faculty of Classics and McDonald Institute for Archaeological Research, University of Cambridge, Cambridge, UK
Laboratory of Landscape Archaeology and Remote Sensing, Department of History and Cultural Heritage, University of Siena, Siena, Italy

Synonyms

Nondestructive archaeology

Definition

Remote Sensing – or *Télédétection* (French), *Fernerkundung* (German), *Percepcion Remota* (Spanish), 遙感 (Chinese) – can be defined as the science of identifying, observing, interpreting, and measuring objects or surfaces without coming into direct contact with them.

In the archaeological process, the scientific community has taken at least two different approaches to the definition of remote sensing. Some archaeologists define it as the technique of obtaining information about objects through the analysis of data collected by sensors (cameras, scanners, imaging radar systems, etc.) that are not in physical contact with the objects under investigation, mostly using spaceborne and airborne instruments. From this point of view, remote sensing differs from ground-based sensing, in which the instruments physically touch the ground surface. A common example of a ground-based instrument is ground-penetrating radar (Doneus et al., 2011).

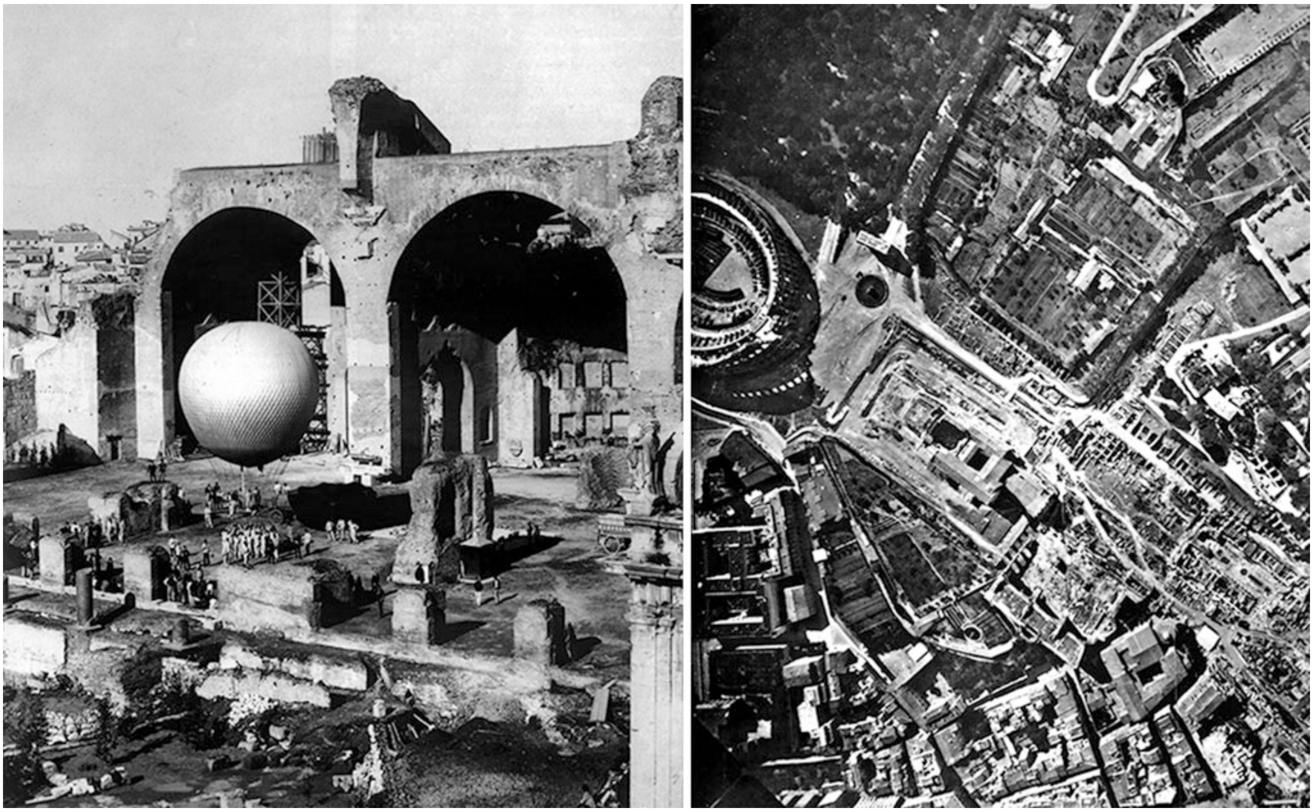
Other archaeologists prefer to include within remote sensing any nondestructive approach to viewing the buried and nominally invisible evidence of past activity. These approaches include spaceborne and airborne sensors (traditional or digital air photographic sensors, technology-based multispectral or hyperspectral scanners, etc.) but also ground-based geophysical instruments (see other entries on geophysics, magnetometry, ground-penetrating radar, and electrical resistivity). Undersea remote sensing can also fall into this category, as can noninvasive techniques such as surface collection or field-walking survey, in the eyes of some archaeologists. Within this interpretation, any method that enables observation of the buried evidence without impacting the surviving stratigraphy is included within remote sensing (Powlesland, 2010).

Introduction

For a long time, remote sensing in archaeological studies consisted almost entirely of aerial photography along with mapping and interpretation of the resulting images. The first application was related to the documentation of archaeological excavations and similar contexts. The earliest episode of air photographic recording, by F. Stolze and F. C. Andreas, took place in 1874 at Persepolis, Iran (Stolze, 1882). In Europe, the Italians played a prominent role in the early history of aerial archaeology, starting with the famous images of the Forum in Rome, taken by Giacomo Boni in 1899 (Figure 1). These pioneering efforts were followed by others along the Tiber near Rome in 1902–1903 and 1908 and then in and around Venice, Ostia, and Pompeii (Boni, 1900; Piccarreta and Ceraudo, 2000).

Similar initiatives also took place in other European countries, particularly in Britain. In 1906, during experiments using an untethered military balloon, Lieutenant P. H. Sharpe took the first aerial photographs of the great megalithic monument of Stonehenge (Bewley, 2002). At this time, the only platform available for aerial photography was the hot air or gas-filled balloon. In this early phase, aerial photography offered a new perspective in the recording of already-known surface features, the purely documentary objective being to obtain a faithful representation of the site or features concerned. Balloons were later used in the 1930s for pioneering photography of the famous excavations at Biskupin in Poland (Rączkowski, 2005). Both balloons and a variety of kite-based systems remain in use to the present day for site-related or locally focused aerial photography.

The Great War of 1914–1918 had a significant impact on the development of a completely new type of platform, the powered aircraft. Along with related advances in cameras and films, aircraft-based aerial photography was exploited as a novel source of intelligence by all combatants. If the number of aerial photographs taken prior to 1914 could be counted in the dozens, then by the end of the war, the UK's Royal Air Force alone had collected about half a million images (Rączkowski, 2001). The war had also introduced a number of pilots and observers to the archaeological potential of aerial photography. In Britain, one of these was O. G. S. Crawford, while another, in a rather different setting in the Middle East, was the expatriate Frenchman Antoine Poidebard. These two men are considered globally as the fathers of aerial archaeology and its application to landscape studies. In 1928, Crawford published (with Alexander Keiller) *Wessex from the Air*, which demonstrated the vast potential of aerial photography and established the main



Remote Sensing in Archaeology, Figure 1 Tethered air balloon used to record the archaeological excavations of Giacomo Boni in the Foro Romano. (Courtesy of Guaitoli (2003).)

principles of the technique – Crawford and Keiller (1928); see also Deuel (1969) and Barber (2011) for accounts of the early days and later development of archaeological air photography.

The Second World War of 1939–1945 brought about methodological and technical developments in both aerial platforms (aircraft) and cameras, and it witnessed the development of new remote sensing techniques such as radar technology, which was not yet used in archaeological contexts. Perhaps the link between the prewar "pioneering" phase and the beginnings of the postwar "interpretative" phase could be identified most clearly with John S. P. Bradford, a former British RAF intelligence officer, who in the months immediately following the cessation of hostilities became involved in aerial photography and archaeological mapping on the Tavoliere Plain around Foggia in southern Italy. There, he and a fellow RAF officer, Peter Williams-Hunt, discovered extraordinary evidence of previously unrecognized landscapes, consisting of hundreds of Neolithic enclosures along with Roman remains, villas, farmsteads, and centuriation, as well as a "lost" town, medieval field systems, mounds, roads, trackways, and various kinds of settlements. However, it was the significance of Bradford's subsequent book, *Ancient Landscapes* (1957), which stands as his greatest achievement, because of the message it conveys about the potential of aerial evidence in archaeological and landscape studies, not just in Italy but also across large swathes of Europe.

In the 1950s, new platforms for Earth imaging became available through the use of satellites and high-altitude aircraft, and new sensors were introduced in the form of near-, medium-, and thermal-infrared imaging systems, along with instruments for the collection of microwave and multispectral data. To take account of the widened perspectives introduced by these new sensors and the early satellites, Evelyn L. Pruitt, a geographer formerly with the Office of Naval Research in the USA, coined a new term, "remote sensing," in the 1950s. In doing so, she added another important phrase to the technical lexicon. The new term, promoted in a series of symposia at the Willow Run Laboratories of the University of Michigan, gained immediate and widespread acceptance.

Although the term itself has a relatively recent origin, the technique has, nevertheless, been used by humans since the dawn of history. Every time we sense our surroundings with our eye-brain system, we are determining the size, shape, and color of objects from a distance by collecting and analyzing reflected visible light. This is all done cognitively without coming into direct contact with the objects that we are observing. In a similar manner, certain snakes use special heat sensors to perceive impressions of their surrounding environment; the snakes detect natural heat signals passively in the same way satellite infrared detectors image the Earth's surface based on its emitted heat. Bats use sound echoes to navigate and to detect prey; similarly radar systems use transmitted radio waves and their reflections to sense a variety of distant objects and surfaces remotely.

Notwithstanding the great improvements in remote sensing during and after the Second World War, the archaeological community continued to rely almost entirely on aerial photography and interpretation of the resulting images for at least the next three decades. The technologies involved in the newer forms of remote sensing were considered to be the "leading edge," reserved for military and other purposes, and it was unusual for archaeologists to make use of them. Eventually, however, remote sensing became more widely used in the field of archaeology, starting in the late 1980s and early 1990s. This period witnessed the application of innovative techniques, including the analysis of satellite imagery; the acquisition through airborne sensors of multispectral, hyperspectral, and radar data; and the use of ground-based geophysical methods, such as magnetometry, electrical resistivity tomography (ERT), and ground-penetrating radar (GPR).

Experience in the following decades, along with technological progress and an increasing understanding of the extraordinary complexity of archaeological contexts, led to the inescapable conclusion that only through the integration of remote sensing techniques with archaeometry and traditional methods such as excavation and ground-based field survey could archaeologists possibly achieve the quantum leap in quality that everyone hoped for and expected. One factor played a central role in the maturing of archaeological remote sensing during this recent period, a factor that is synonymous with the integration and management of the wide range of information resulting from the subject's inherent complexity: geographical information systems or GIS.

While engineers, physicists, and computer scientists improved the quality or effectiveness of individual systems, sensors, and techniques or designed entirely new ones, archaeologists through the application of GIS started thinking *beyond* the individual image or dataset to produce and map broader integrations, and therefore interpretations, and in this way they brought together a wide variety of data. The stratification and overlaying of information within the single "container" of GIS provided an essential tool in the search for and development of a new and more integrated approach to the representation and interpretation of evidence from the past.

Currently, the use of remote sensing in archaeology is growing rapidly at universities, some of which have created highly specialized departments and institutions with undergraduate, graduate, postdoctoral schools, and specific research programs. This trend is also seen at institutions aimed at the protection and conservation of archaeological heritage, as, for instance, in the nationwide mapping of air photographic evidence in England (see below). International associations, such as the Aerial Archaeology Research Group (AARG) (http://www.univie.ac.at/aarg) and the International Society for Archaeological Prospection (http://www.brad.ac.uk/archsci/archprospection/), have also played a significant role in the dissemination of these methods and techniques.

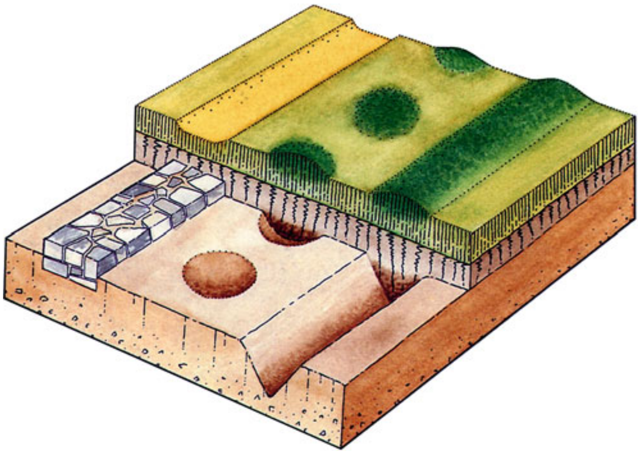
Principles of remote sensing

Remote sensing may reveal archaeological features *directly*, where they are still extant (albeit perhaps heavily eroded) in the form of topographical variations. Alternatively, when they no longer exist above the ground surface, they may be revealed *indirectly* in the form of variations in the coloring and height of the vegetation. These may appear as visible discontinuities in bare soil exposed by agriculture, erosion, or other surface indications or in an intermediary form, as micromorphological discontinuities where the features are buried (Wilson, 2000).

When sites are extant, remote sensing can play a special role in documenting their general form and constituent parts from a high-level viewpoint, allowing rapid mapping with the aid of purpose-designed computer programs (Remondino, 2011). Many sites, of course, could alternatively be mapped from the ground, but the use of remote sensing data can be extremely valuable for mapping sites and features which, for one reason or another, are not readily accessible for ground-based survey.

The *indirect* identification of archaeological evidence is particularly valuable in the discovery of previously unrecognized sites and features. The main principle in this context is the capacity of techniques like aerial photography, LiDAR, radar, or thermal-infrared imaging to recognize evidence that provides indirect indications in the natural soil of past human activity. Several methodologies have been developed to identify relative (though never absolute) environmental variations for this purpose. The recognition of archaeological features represented by indirect evidence exploits a number of interlinked "phenomena" (Musson, 1994), including:

1. Variations in the coloring, height, or density of arable crops or other vegetation. These have variously been described as *vegetation marks* or (more commonly) *cropmarks*. They represent one of the most striking tools for the discovery of previously unrecorded sites. Cropmarks appear as differences of height and/or color in crops that are under stress, usually based on the lack of water or some other nutrient. This is more likely to occur in light and well-drained soils, above soft and permeable rocks or gravels. As a result, the distribution across countries, regions, and local areas is irregular. Cropmarks appear most frequently in ripening grain, especially when the weather has been dry at critical stages of growth or maturing. In these conditions, cropmarks can be seen over a period of 2–8 weeks during the late stages of ripening or for shorter periods in



Remote Sensing in Archaeology, Figure 2 The formation of cropmarks: crops grow taller and ripen later over the deeper, more nutritious, and damper soil of a buried ditch or large pit. Growth is stunted, and the ripening of the crop occurs earlier in shallower soil above buried walls or other impervious deposits. Ditches and pits create *green* marks in the *yellowing* crop. Walls and similar obstructive features cause *yellow* marks in the *green* crop. Both can persist as *yellow-on-yellow* marks in the ripened crop. (Courtesy of Royal Commission on the Ancient and Historical Monuments of Wales.)

the early stages of growth (Figure 2). During damper years, the crop may never come under enough stress to produce cropmarks, even where they have been regularly seen in the past. Cropmarks occasionally appear at other times of the year in a wide variety of vegetation: cereals, grass, root crops, green fodder crops, weeds, and various flowering plants.

2. Differences in bare soil exposed by agricultural activity or erosion. These are usually known as *soil marks*. They appear as changes of color, texture, or dampness in the surface of the soil and reflect subsurface features, such as ditches or wall foundations. The marks may appear for only short periods as the soil dries or reflects the sun in particular ways. The main difficulty in detecting them lies in recording them at the right moment, especially when the soil is damp and fresh from the plow or harrow.
3. The effect of light and shade, producing what have sometimes been described as *shadow marks*. In this case, shadow and highlight are used to emphasize physical features which still exist but may be almost invisible on the ground, such as the barely detectable earthworks of prehistoric field banks or heavily eroded burial mounds. Archaeological air photographers, therefore, take advantage of low sunshine in the winter or of early-morning/late-evening light at other times of the year. This "low-light" or "shadow" technique is particularly effective in upland areas where there has been less erosion by modern plowing. It can also be productive, however, in lowland zones, throwing very slight patterns of topographical variation into relief by the play of light and shade, thereby making the overall form of the archaeological feature more intelligible.
4. Special conditions created by frost, ice, and floods create situations that can offer good opportunities for archaeological air photography. A thin covering of snow, for instance, suppresses distracting color and provides excellent conditions for low-light photography. The differential melting of frost by sun or wind, or the persistence of ice and snow above buried ditches at the end of a cold spell, can also reveal otherwise unsuspected subsurface features. Flooding may redefine old river courses and explain the location of roads or farmsteads in a way that could otherwise be achieved only by painstaking survey on the ground. Prolonged drought can produce cropmarks in otherwise unresponsive grassland, revealing evidence that is rarely, if ever, available at other times.

Important parameters in remote sensing

The success of remote sensing in archaeological applications depends not only on the date of data capture but also on the quality of the collected evidence. At least four parameters are involved here: spatial, spectral, radiometric, and temporal resolutions (Lillesand and Kiefer, 1994).

Spatial resolution relates to the level of detail that is visible in the image; it is dependent on the resolving power of the sensor and the distance between platform and object. In a raster image, spatial resolution depends on the area of ground surface that is represented by each recorded pixel. Typically, pixels may correspond to surface areas ranging from 30 m square to 1 m square, or even as little as 5 cm square. Spatial resolution represents one of the most important parameters for archaeological remote sensing, in that it is critical to determining the size of archaeological features that can be identified in the resulting data.

Spectral resolution refers to the range width and number of specific dimensional units to which a sensor is sensitive. The limited spectral interval of the electromagnetic spectrum visible to the human eye (wavelengths from about 390–750 nm) is greatly extended by the use of photoelectric sensing devices. This increase in the capability of recording different regions of the electromagnetic spectrum demonstrates a desire to exploit their full potential, separating information on different layers (bands) to produce multispectral images (2–10 spectral bands) or hyperspectral images (10–200 spectral bands). This quality may play an important role in the detection of archaeological features.

Radiometric resolution refers to the number of different intensities of radiation that the sensor is able to distinguish. Typically, this ranges from 8 to 14 bits in each band, corresponding to 256 levels of the gray scale and up to 16,384 intensities or "shades" of color.

Temporal resolution relates to the frequency of overflights by the satellite, aircraft, or any other recording platform. It is extremely relevant in archaeological studies, making it possible in some instances to monitor landscape or site transformations over time (measured in days, years, or even decades). “Historic” data from remote sensing, such as early aerial photographs or the data from the early generations of satellites, can be very valuable in providing the only available source of information about long-term landscape transformations over time.

Image examination and archaeological interpretation

Remotely sensed images contain a detailed record of features on the ground at the time of exposure, relating both the modern landscape and that of the past. In the process of interpretation, the archaeologist examines the images systematically and often draws on other relevant material, such as maps and reports of field observation. The interpretation derived from this study aims to “read” and make sense of the phenomena and features appearing in both the modern and the “ancient” landscape and to distinguish between them. The basis for sound interpretation is a secure understanding of the peculiarities of the modern landscape in the area concerned. The identification of the present pattern, and its constituent parts, can draw attention to “nonconforming” elements, which might form part of earlier features, sites, or landscape patterns. In carrying out the systematic initial examination, attention is paid to a variety of basic characteristics or variations of them, such as shape, size, pattern, tone, texture, shadow, topographical position, and association (Lillesand and Kiefer, 1994).

Aims and peculiarities of archaeological remote sensing

Archaeology and its use of remote sensing have often been compared with medicine and medical diagnostic procedures. The development of the clinical picture, as well the archaeological process, comes through understanding of the personal and family history and through the developmental story of archaeology itself. Semiotics, representing the analysis of phenomena and signs visible from outside, finds a close parallel with field-walking survey and surface collection. The last stage of medical diagnosis involves instrumental analysis (evidence-based medicine) through the use of laboratory tests, and this phase finds parallels with archaeometry. Special equipment or tools, such as ultrasound and radiology, are used, and these are in a real sense similar to the remote sensing tools used in archaeology.

The main aims of remote sensing in archaeology can be identified as follows:

- The documentation of archaeological contexts in great and objective detail
- The acquisition of information on buried deposits sometimes completely invisible at ground level, describing in some detail the metrical, geometrical, and physical-chemical properties of the subsurface features
- The well-balanced and representative recording of both positive and negative kinds of archaeological evidence
- The monitoring, from very large scale to small scale, of landscape transformations, allowing the development of conservation and planning policies
- The mapping of archaeological data, interpretations, and reconstructions through the use of GIS technology that can cope with the inherent complexity of past landscapes and archaeological sites

Main weaknesses

Remote sensing in archaeology is subject to a number of limitations. In the case of optical sensors operating in the visible part of the electromagnetic spectrum, the higher limit can be summarized by the concept of serendipity. Serendipity is the discovery of something unsought and unexpected, but not by chance alone. The positive result must be the outcome of planned experiments, taking place in the framework of systematic scientific research. In the case of archaeological remote sensing, the serendipitous recovery of information is influenced by a number of parameters: pedology, climate, cultivation patterns, the plants or crops being grown, the historical development of the landscape, etc. Archaeologists understand from a theoretical point of view the scientific principles that make underground archaeological features visible at the ground surface (Jones and Evans, 1975). They cannot, however, control the environmental and anthropological factors that affect the way subsurface archaeological features modify the appearance of bare soil or vegetation to reveal their presence. As a result, the distribution of archaeological features in remotely sensed evidence is as much a reflection of these influencing factors as it is of the real presence or absence of archaeological sites (Figure 3).

To a certain extent, the techniques that rely on portions outside the visible part of the electromagnetic spectrum – such as near-, middle-, and thermal-infrared, radar, LiDAR, and geophysical prospection – can also be affected by serendipity, though generally the influence on these techniques is less substantial.

Systems and methods

Remote sensing systems and related methods of data analysis are numerous and have traditionally been divided according to the platform used (satellite, aerial, terrestrial, etc.) and the type of sensor employed (optical, thermal, LiDAR, radar, magnetic, etc.).

Satellite imagery

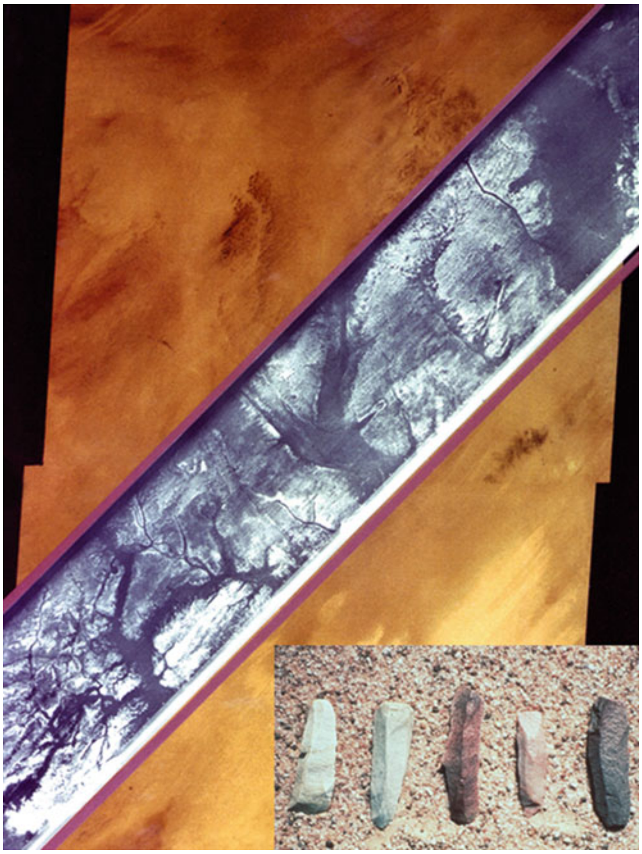
In 1957, the Soviet Union (USSR) put the first satellite, Sputnik 1, into orbit, and the era of satellite remote sensing began. The first *systematic* satellite observation of the Earth was undertaken by the meteorological satellite

Remote Sensing in Archaeology, Figure 3 Above *left*, oblique aerial photograph showing a large grain cultivation field where cropmarks are clearly visible (details above on the *right* side); they are interpreted as features of a Roman villa. The photographs were collected in 2005 during the ripening season when cropmarks are at their best visibility for archaeological prospection. *Bottom left* and *right*, oblique aerial photographs showing exactly the same area photographed 2 years later (2007). The aerial survey was carried out during the cropmark season, but this time serendipity did not work. As a result, no features are visible in the aerial photography. This is a paradigmatic example showing how distribution of archaeological features is as much an echo of serendipity as it is of the real presence or absence of archaeological sites.

TIROS-1 in 1960 by the USA space program. The era of satellite photogrammetry started in 1960 with the CORONA military reconnaissance program, also an American project. The use of satellite images for more general mapping and measurement studies began in 1962 with the design and launch of the CORONA KH-4 satellite (Galiatsatos, 2014).

Civilian satellites started with the advent of Landsat-1 in 1972. Later, several satellite sensor systems similar to Landsat were launched, such as the French SPOT HRV and the Indian LISS systems. In this period, applications to archaeology were constrained by the poor geometric resolution (about 20 m per pixel) and use of the images being restricted to high-end scientific research laboratories. In archaeological as well as other contexts, the satellite imagery available at this time was mainly used to study or characterize the environmental background and current agricultural patterns or to generate cartography in areas where maps were not available, as in parts of Central Asia, the Near East, Africa, and Central America (Musá et al., 1977; Khawaga, 1979).

Other highlights in the history of satellite remote sensing include the launch of radar systems into space, the proliferation of weather satellites, a series of specialized devices dealing with environmental monitoring or with thermal and passive microwave sensors, and the more recent hyperspectral sensors. For instance, radar imagery attracted global media attention following the discovery of such things as the lost city of Ubar in southern Oman (Bloom, 1992) and the so-called radar rivers (Figure 4), former riverbeds still extant beneath the sands of the Sahara (McCauley et al., 1982). Since the turn of the millennium, the archaeological use of satellite data has become both more widespread and more common. Despite long-lasting and important work by a small number of scientists and archaeologists from the 1970s



Remote Sensing in Archaeology, Figure 4 Above: Shuttle Imaging Radar-A flew on the second flight of Space Shuttle Columbia in 1981. The images show SIR-A radar over Landsat Multispectral Scanner in southwestern Egypt where thin sand cover (0 to a few meters) obscures an underlying, older fluvial landscape. L band (23 cm) radar images through 2+ meters of dry sand show buried integrated drainage systems (Courtesy of R. G. Bloom, JPL-NASA); below: Neolithic stone artifacts abundant near the "radar rivers" reveal evidence for significant human presence. (Courtesy of R. G. Bloom, JPL-NASA.)

onward, the main change that has influenced the development of satellite archaeology has been a radical improvement in the geometric resolution of the images.

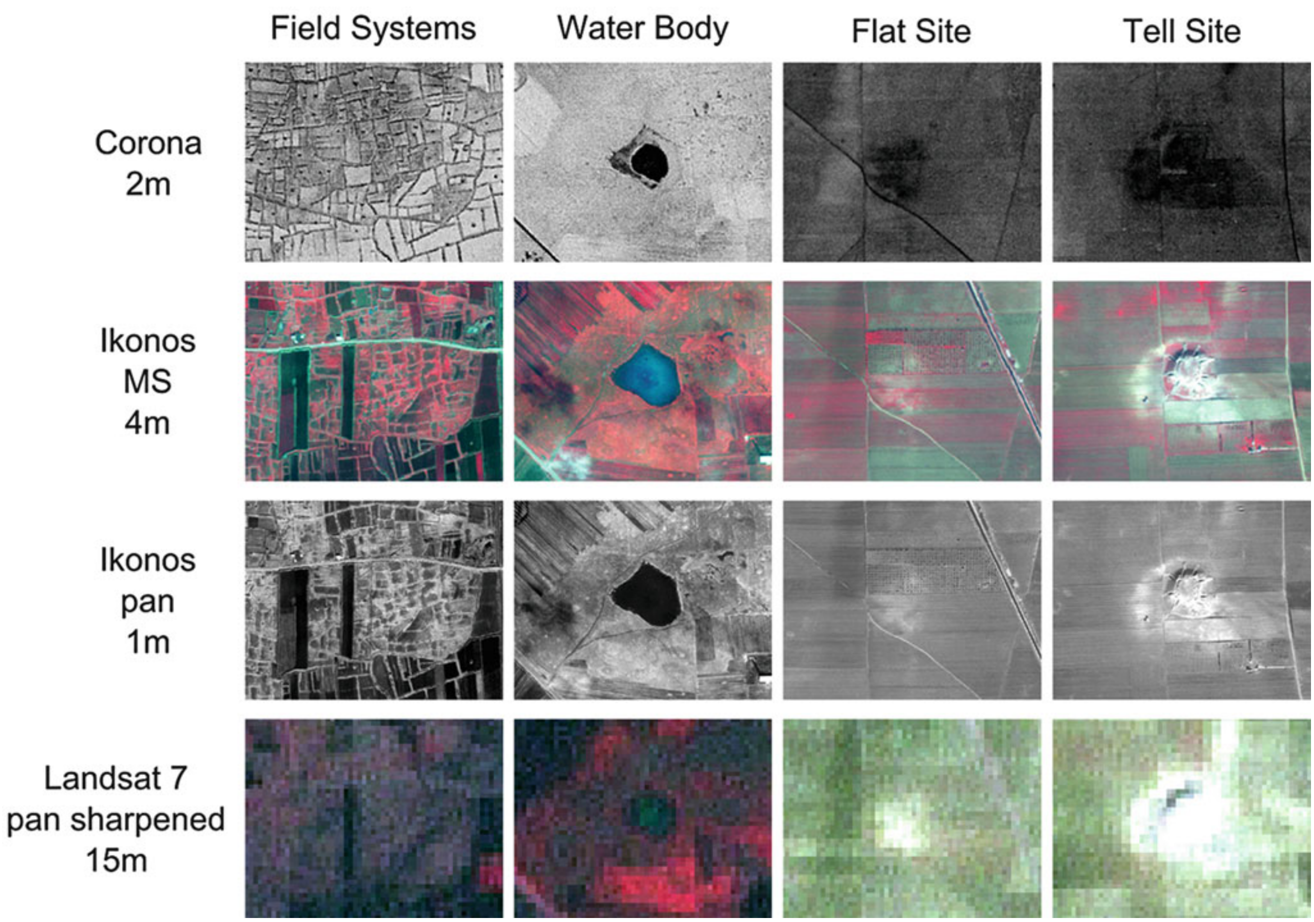
The development of very high-resolution satellite imagery (HRSI) began with the appearance of the first commercial satellites (Parcak, 2009; Lasaponara and Masini, 2012). The first successfully launched commercial satellite was IKONOS-2 in 1999. This was followed by QuickBird in 2001, OrbView-3 in 2003, and later by KOMPSAT-2, EROS-B1, and Resource-DK-1 in 2006. In the last 15 years, the resolution of available satellite images has improved from 20 m per pixel (SPOT) to 0.40 m per pixel (GeoEye-1, launched in September 2008), representing a 2,500 times increase in the capacity to detect small objects (Figure 5).

The opportunities for archaeological applications have, therefore, vastly increased, though there are still some significant limitations.

- *Scheduling*: There are still difficulties (and costs) in scheduling image capture to coincide with archaeologically advantageous conditions or time of year. Archaeologists need more flexibility to plan image capture during the right time windows, e.g., during the cropmark season at the locality concerned.
- *HRSI spectral resolution*: This is mainly characterized by the use of only three bands in the visible part of the spectrum and a fourth in the near infrared.
- *Geometric resolution*: In contrast to these limitations, the newest GeoEye-2 satellite (on July 31, 2014, DigitalGlobe announced that the GeoEye-2 satellite sensor will be renamed WorldView-4) due for launch from 2013 onward and the "next-generation" commercial satellites – planned for launch during 2016 – will have a spatial panchromatic resolution of 30 cm and spatial multispectral resolution of 1.20 m. Many archaeologists, however, feel that they need something closer to the 5 cm or higher resolution provided by traditional aerial photography.

As a final observation, it should be pointed out that a casual observer wandering through a library, particularly in the USA, might be forgiven for believing that satellite remote sensing is the prime technique for archaeological research. This is not, in fact, the case. According to Powlesland, "for every 'site' identified from space, thousands have been identified through air-photography" (2010, 9). In Europe, aerial photography has been used to observe and document archaeological landscapes for more than a century, and this method remains by far the most significant contributor to the ever-expanding archaeological record. For instance, from the papers presented at the annual meetings of the Aerial Archaeology Research Group, it is possible to see the tremendous impact that aerial survey and photography are having in European countries where, until the political changes of the early 1990s, flight restrictions made photography from light aircraft virtually impossible.

There has been extensive use of satellite imagery, *in the absence of* available data of a higher standard from less costly and more effective remote sensing techniques such as aerial photography, geophysical prospection, airborne laser scanning, and multispectral or hyperspectral data capture. It is important to recognize, however, that a significant but often underemphasized contribution of satellite imagery is its worldwide coverage and, therefore, (1) the impact such imagery has on the analysis of large geographical areas and (2) the scale that can be incorporated within "landscape" studies. The combination of satellite imagery and "virtual globe" geographical information systems, such as Google Earth, makes possible the observation of very broad areas of the planet at a high level of detail – an unimaginable concept only a few years ago.



Remote Sensing in Archaeology, Figure 5 Comparison of satellite sensors with different spatial and temporal resolution: CORONA 1969, IKONOS 2002, and Landsat 1999. (Courtesy of Beck, 2011.)

Airborne remote sensing

Leaving aside photography from light aircraft for the moment, airborne remote sensing at its more sophisticated and commercial levels uses downward- or sideward-pointing sensors mounted on specialist aircraft so as to obtain vertical or oblique images of the Earth's surface. One advantage, compared to satellite remote sensing, is the capacity to achieve very high spatial resolutions, between 20 and 5 cm per pixel. The disadvantages are lower areal coverage and higher cost per unit of ground surface. This kind of remote sensing is not cost effective for mapping very large areas, such as whole continents, though it has been used (cumulatively and over considerable time) to map whole countries and regions. Airborne remote sensing missions are usually carried out as single (but occasionally repeated) operations, whereas Earth observation satellites offer the possibility of truly continuous monitoring of the planet's surface. Both analog and digital photography are commonly used in airborne remote sensing. Multispectral and hyperspectral imaging, synthetic aperture radar (SAR), and LiDAR scanning are also carried out from airborne platforms.

Air photography

Archaeologists use two types of air photography: "oblique," or perspective views, and "vertical" photography that point straight downward at the Earth's surface. Vertical photography (originally analog, but now more frequently digital) is taken with sophisticated cameras from specially equipped aircraft, mainly for survey and mapping purposes. It is relatively expensive, and archaeologists can rarely afford to commission it for their own research purposes (Musson, 1994). Therefore, archaeologists draw on vast collections of air photographs already available in existing archives (Figures 6 and 7). During the Second World War, approximately 50 million aerial photographs were taken (Going, 2002). In modern Europe, public services collect perhaps millions more frames each year.

Oblique photographs are generally taken by archaeologists themselves, from the open window of a small aircraft hired from a local airfield (or occasionally owned by the archaeologists themselves or by their employers). The cameras and film are quite simple and inexpensive. While vertical photography records the whole of the landscape,

Remote Sensing in Archaeology, Figure 6 Vertical historical aerial photography collected in 1955 in the countryside of Foggia (southern Italy). The photography shows clear features of Neolithic enclosures, medieval mounds, and field systems. (Courtesy of Guaitoli, 2003.)

oblique photography is selective and covers only what the photographer sees and judges to be archaeologically significant (Figure 8). What he or she fails to see, or understand, inevitably fails to be recorded. Vertical photography, therefore, has a special value in the study of the whole landscape, or of settlements in their broader context. Oblique photography, by contrast, is unrivaled in recording individual sites of historic interest, the more so because the photographer can choose the time of day or year and the kind of lighting that will illustrate or reveal archaeological features to best advantage (Figure 9).

Vertical photographs do, of course, contain archaeological information, but more by accident than design, and for the most part at shadow-free times of the day or year that suit mapping, rather than specifically archaeological recording. Nevertheless, there are examples of extraordinary results being achieved through vertical photography carried out explicitly for archaeological proposes, such as when conditions for cropmark or soil mark recording are at their best.

Austria, Italy, and the UK all document cases confirming that if vertical coverage can be arranged within the best timeframe for the visibility of archaeological evidence, then the whole area, along with all of the sites that are visible at the moment of photography, can be depicted in stereo pairs of photographs that provide a 3D replica of the target landscape. This kind of documentation can lead to a vast improvement in the analysis and understanding of past landscapes (Doneus, 2001; Guaitoli, 2003; Palmer, 2007). The main difficulties with this practice are its relatively high cost and the short time that is available to plan and execute vertical coverage on the limited number of occasions when the conditions are ideal for recording.

In their professional work, archaeologists use the two types of aerial photography, vertical and oblique, more or less equally. For instance, the comprehensive National Mapping Programme for England (NMP), begun in the late 1980s and still in progress at English Heritage, had covered approximately forty percent of England by April 2009. Teams of experienced archaeological air-photo interpreters working on the NMP have unlocked information held in millions of vertical and oblique aerial photographs, mainly taken since 1945. NMP projects continue to provide information and synthesis for archaeological sites and landscapes of all periods from the Neolithic to the twentieth century, priority being given to those areas of the country that are under the greatest threat or are poorly documented (Horne, 2011).

Remote Sensing in Archaeology, Figure 7 Vertical historical photography collected over Cerveteri in 1930. Visible in the photograph are a number of *white round* features distributed nearly everywhere and corresponding with round barrows. (Courtesy of Guaitoli, 2003.)

Remote Sensing in Archaeology, Figure 8 Oblique aerial photography collected in 2005 at Vulci (Italy). The photograph shows clearly a substantial number of square and other geometrical features related to the settlement area of the Etruscan and Roman city of Vulci.

Multispectral and hyperspectral scanning (MSS and HSS)

The effectiveness of aerial photography is limited by the differential visibility of cropmark, soil mark, or earthwork evidence in response to conditioning factors, as mentioned above. It is widely recognized that multi- and hyperspectral imagery can address some of these contextual problems because they are potentially more sensitive to changes in vegetation status than the visible or panchromatic ranges (Donoghue, 2001; Shell, 2002). Indeed,

Remote Sensing in Archaeology, Figure 9 Oblique aerial photography collected in 2003 in the countryside of Foggia (Italy). The photograph shows stratified ancient landscapes. It is possible to recognize at least two main periods: prehistoric and Roman. Two Neolithic circular enclosures (single and double ditch enclosures), probably related to different chronological phases, are distinguishable (*bottom* and *top*). Over the Neolithic features are a number of traces related to a centuriation pattern (road and cultivation systems) in association with a settlement (*bottom left*), which is also plainly observable.

multispectral or hyperspectral sensors are able to look simultaneously at a wide range of wavelengths, many of which lie in the near- and shortwave infrared spectrum, and add important collateral information to the visual wavelengths. These factors thus improve the ability to discriminate vegetation stress, soil moisture, and temperature variations (Beck, 2011).

Pioneering studies have been undertaken in the American Southwest using airborne thermal imaging to define areas of past agriculture more clearly than was possible with black-and-white photography (Schaber and Gumerman, 1969). These early studies were carried out to assess the efficacy of multispectral data for recording areas of Pueblo Indian archaeology and their environmental settings at Chaco Canyon in New Mexico and elsewhere (Lyons and Avery, 1977; Lyons and Mathien, 1980; Avery and Lyons, 1981).

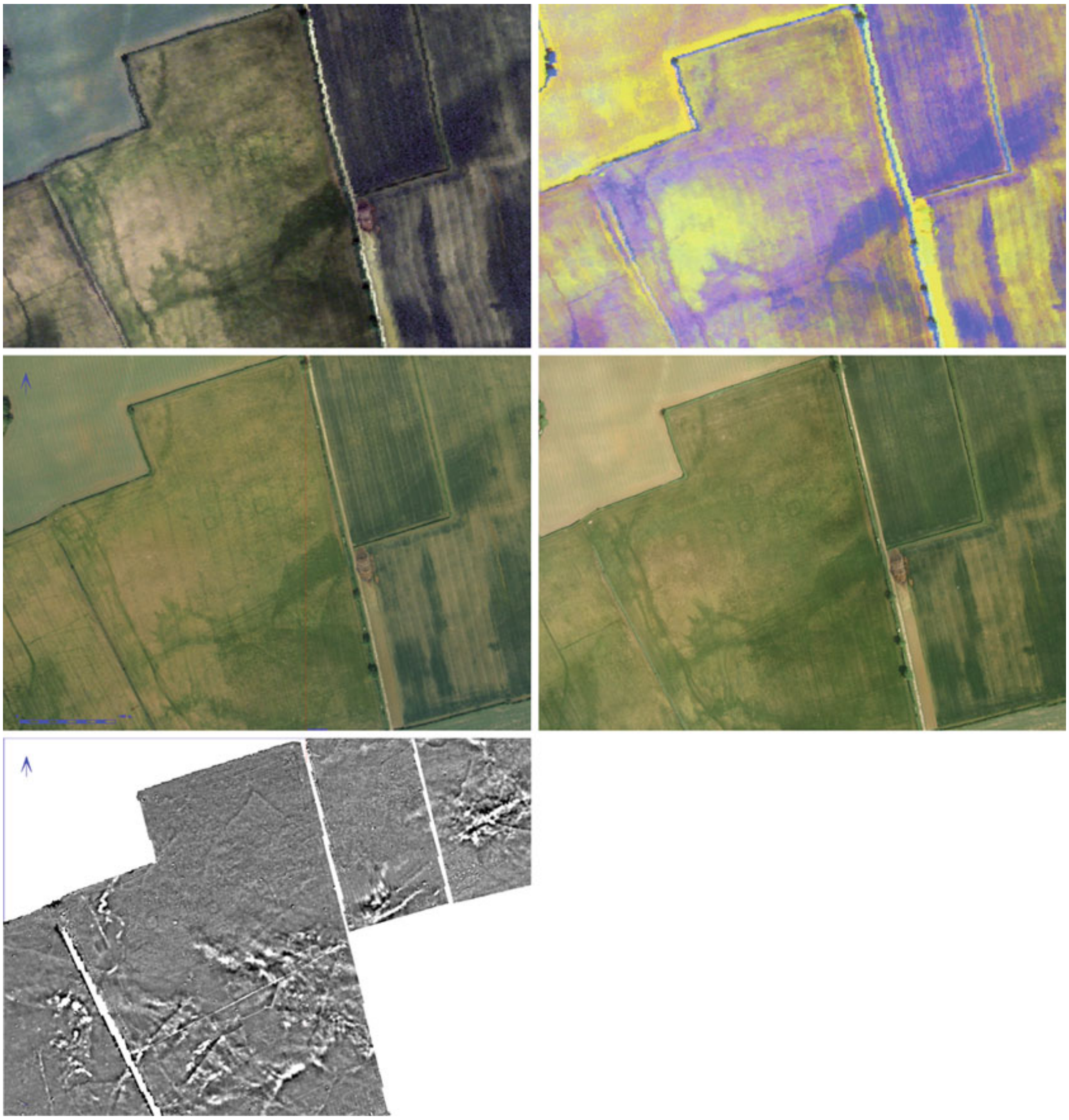
In Europe, thanks to the development by national research agencies of multi- and/or hyperspectral systems, Britain and Italy are recognized as leaders in the field, having carried out a number of important studies from the 1990s. In Britain, airborne multispectral scanners have been used to assess the archaeological potential of multispectral data at a number of sites. This imagery has complemented vertical photography and revealed new information in the infrared wavelengths in places such as the former wetland environments of the Fenlands in eastern England and the Vale of Pickering farther to the north (Figure 10; Powlesland and Donoghue, 1993). These studies showed that the red and infrared images provide good definition for soil marks and cropmarks and that the near- and shortwave infrared wavebands are particularly sensitive to plant health and, therefore, to the effective detection of water stress in vegetation (Shennan and Donoghue, 1992). In Italy, experiments have been carried out mainly by geologists and earth scientists in the use of the airborne thematic mapper (ATM) multispectral scanner to detect paleoenvironmental patterns and geomorphological features, such as ancient river channels, areas of marshland, and evidence of coastal change.

The increasing availability of hyperspectral imagery, as well as thermal imagery, presents very significant possibilities. In Britain, the main data source of multi- and hyperspectral data is the Airborne Research and Survey Facility managed by the Natural Environment Research Council (NERC), while in Italy this research has been conducted through the National Research Council (CNR). Since the late 1990s in both countries, researchers have been applying multi- and hyperspectral imagery in landscape analysis (Cavalli et al., 2003; Shell, 2005; Traviglia, 2007; Aqdus et al., 2008). The general trend, emerging from a substantial number of case studies in differing physical and cultural contexts over the past two decades, has demonstrated that these kinds of sensor can be a valuable resource, complementing information obtained through other remote sensing techniques and adding specific support in the identification of features in the non-visible domain (Donoghue et al., 2006).

Currently, a major disadvantage, however, is the poorer resolution of the multispectral and hyperspectral data, generally between 3 and 4 m per pixel depending on the characteristics of the sensor and the altitude of the aircraft. Within archaeology, this level of resolution is suitable only for the detection of large-scale features.

Synthetic aperture radar (SAR)

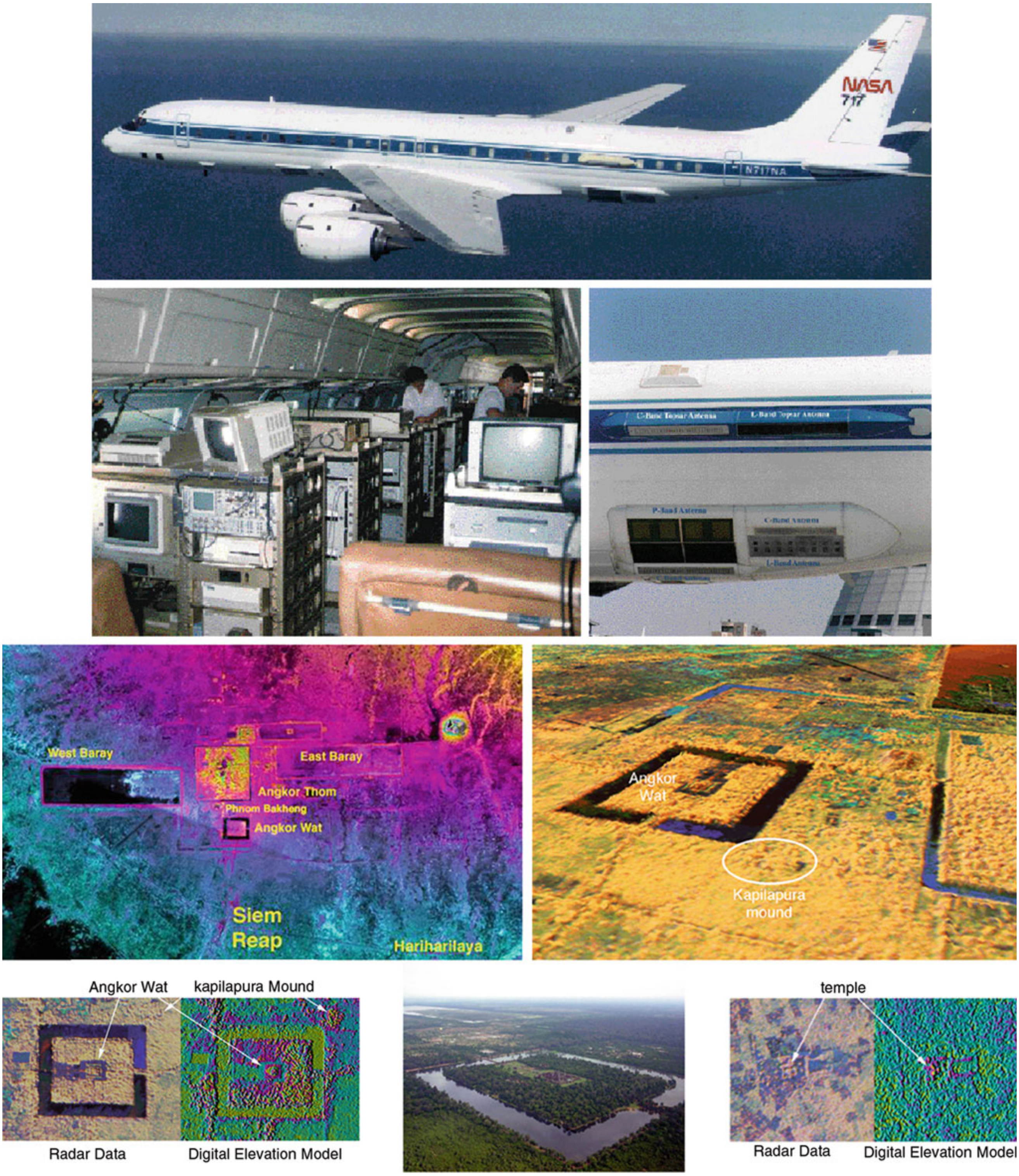
Radar is an active microwave sensing system, sending directional pulses of electromagnetic energy and detecting the presence and position of objects by analyzing the portion of the energy reflected back to the transmitter (Lillesand and Kiefer, 1994). A key advantage is its ability to penetrate through cloud, haze, light atmospheric precipitation, and smoke, making this an “all weather” sensor. The system has a variety of applications in archaeology (Figure 11).



Remote Sensing in Archaeology, Figure 10 Images from the Daedalus 12 band multispectral scanner flown by the Natural Environment Resource Council (NERC) covering a field in West Heslerton, Vale of Pickering, North Yorkshire, UK. The principal features documented in the images include a number of Iron Age square ditched barrows and a prehistoric trackway. (Courtesy of D. Powlesland, Landscape Research Centre.)

From the end of the 1970s, radar has been used for archaeological prospection in regional surveys to detect cultural, natural, and anthropic features (Adams, 1980; Pope and Dahlin, 1989; Sever, 1998). It has also been used for paleolandscape analysis (McHugh et al., 1989), as well as in ecosystem studies and cultural heritage monitoring (Moore et al., 2007). The most important work in this field has been carried out in the USA (Wiseman and El-Baz, 2007), particularly by the NASA's Jet Propulsion Laboratory at Caltech (JPL/NASA). In this context, protocols have been developed for using synthetic aperture radar, or SAR, in the recording of archaeological sites for cultural resource management so as to reduce the risk of costly delays during construction projects (Comer and Blom, 2007).

The application of radar imaging in archaeology is still fairly limited, especially in Europe, where archaeologists and remote sensing scientists have focused more attention on LiDAR, multispectral, and hyperspectral systems. Generally speaking, the main limitation of radar systems is the relatively high cost of commissioning it from a commercial contractor. The maximum penetration of the signal into the soil can be as much as 3–5 m, but this requires very dry ground conditions and fine-grained soil.



Remote Sensing in Archaeology, Figure 11 (Continued)

Specialized training is also essential in image processing and archaeological data interpretation (Holcomb and Shingiray, 2007).

Light detection and ranging (LiDAR)

Airborne LiDAR measures the relative height of the ground surface and other features (such as trees and buildings) across large areas of landscape with a resolution and accuracy hitherto unattainable except through labor-intensive field survey or photogrammetry (Remondino, 2014a). It provides, for the first time, highly detailed and accurate digital 3D models of the land surface at meter and submeter resolution. LiDAR operates by using a pulsed laser beam which is scanned from side to side as the aircraft flies over the survey area, measuring by the length of the time that the signal takes to return to the aircraft between 20,000 and 100,000 points per second to build an accurate, high-resolution model of the ground and the features upon it.

Airborne LiDAR was conceived in the 1960s for submarine detection, and early models were used successfully in the early 1970s in the USA, Canada, and Australia. The possibility of using the technique for archaeological recording was first recognized in the USA thanks to pioneering research in the vicinity of the Arenal Volcano in Costa Rica under the leadership of Tom Sever. In an archaeological study in 1984, Sever and his colleagues used LiDAR, TIMS (thermal infrared multispectral scanner), SAR, and color infrared photography to detect pathways of prehistoric settlers and document trade routes and movement between settlements (Sheets and Sever, 1991).

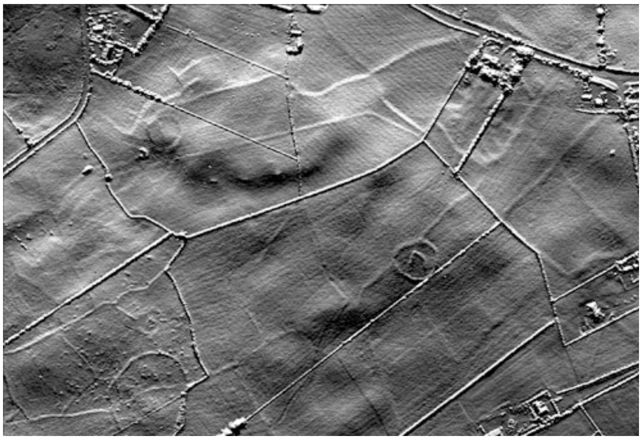
In Europe, the potential of LiDAR applications in archaeology was first discussed at a workshop in Leszno, Poland, in November of 2000. This related to a survey covering the River Wharfe in Yorkshire, which revealed evidence for the survival of a Roman earthwork fort that had previously been thought completely leveled by plowing (Holden et al., 2002). A few years later at Ghent University in Belgium, Robert Bewley, then Head of English Heritage's Aerial Survey Unit, argued that ". . .the introduction of LiDAR is probably the most significant development for archaeological remote sensing since the invention of photography" (Bewley, 2005, 25).

In the following years, LiDAR applications have been developed widely around Europe and particularly in the UK, Austria, France, Germany, Norway, and Italy. Currently, the principal advantage of LiDAR survey for archaeologists is its capacity to provide a high-resolution digital elevation model (DEM) of the landscape that can reveal micro-topography that is virtually indistinguishable at ground level because of erosion by plowing (Figure 12).

An extremely important characteristic of LiDAR is its ability to penetrate woodland and to reveal features that are not distinguishable through traditional prospection methods or that are difficult to reach for ground-based survey (as, for instance, in work at Leitha Mountain, Austria, described in Doneus and Briese, 2006). There have been other notable applications at Elverum in Norway (Risbøl et al., 2006), at Rastatt in Germany (Sittler and Schellberg, 2006), in the Stonehenge landscape and at other locations in the UK (Bewley et al., 2005; Devereux et al., 2005), and, returning to the Americas, at Caracol in Belize (Weishampel et al., 2010). It is worth noting that interest in this technique is not limited to its potential for penetrating woodland areas but also for its contribution to the study of open contexts, such as pastureland and arable areas. In these zones, as under woodland cover, the availability of extremely precise digital models of the ground surface will make it possible to highlight every tiny variation in level and, by using computer simulations, to change the direction or angle of the light and/or to exaggerate the value of the Z-coordinate (height).

Techniques have been developed for the digital removal of "modern" elements such as trees and buildings so as to produce a digital terrain model (DTM) of the actual ground surface, complete with any remaining traces of past human activity (Figure 13). Initial LiDAR pulses reflect from tree canopies or denser branching just beneath, but last pulses can reflect off the ground surface. If these last pulses are used exclusively, the indicators of covering vegetation can be largely eliminated. At present, the cutting edge of LiDAR applications in archaeology is

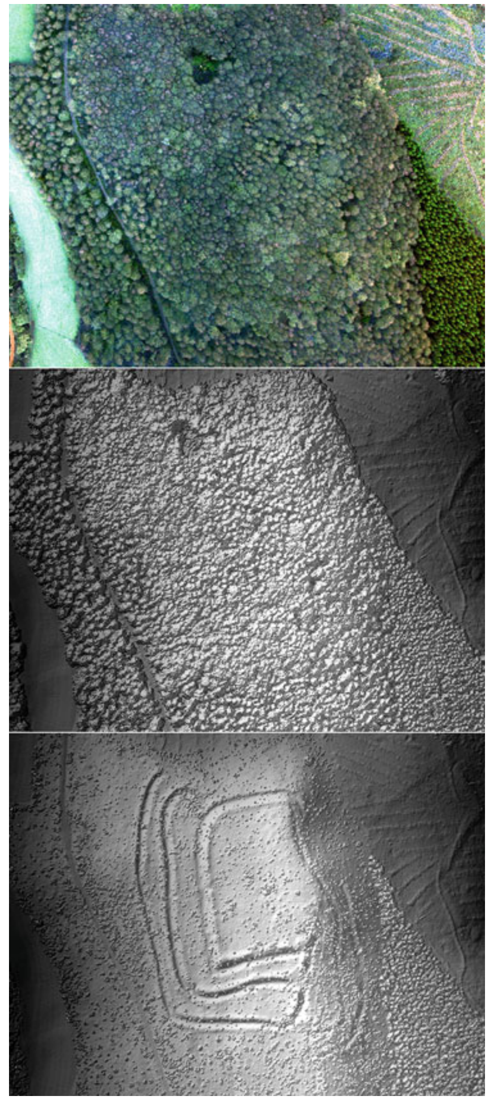
Remote Sensing in Archaeology, Figure 11 Top: Flying Laboratory AIRSAR instrument (panels behind wing) mounted aboard a modified NASA DC-8 aircraft. During data collection, the plane flies at 8 km above the average terrain height at a velocity of 215 m per second. Second row: AIRSAR-JPL's experimental Airborne Synthetic Aperture Radar System. POLSAR-3 wavelengths and full polarization diversity help characterize targets P, L, and C band at HH, HV, VH, and VV polarizations' 3 modes 20, 40, and 80 MHz bandwidth. Resolution increases with bandwidth while swath decreases 80 MHz L, band resolution is 1.7 m, 40 MHz is 3.3 m, and 20 MHz is 6.7 m. Swath width is 5 km at 80 MHz, 10 km at 40 MHz, and 15 km at 20 MHz. TOPSAR generates Hi Res DEMs (digital elevation models) at two wavelengths. Cross-track interferometry L and C band digital elevation models (DEMs) postings at 5 m (40 MHz), 1–3 m height accuracy. Second and third rows: Angkor Wat is a major religious/urban center and has a sophisticated associated water system, ~ninth to fifteenth centuries. The population peak estimate is perhaps one million. Angkor region imaged by SIR-C and AIRSAR. The AIRSAR campaign also collected high-resolution TOPSAR DEMs. Collaborative work advances historical understanding thanks to the detection of previously unknown structures. Angkor lessons: archaeological structures sometimes show both in radar images and DEM but often show only in DEM providing water management insight. From *left* to *right*: Angkor Wat religious/urban center general view. Angkor perspective view: AIRSAR on TOPSAR DEM. Angkor Wat and Kapilapura mound: RADAR data and digital elevation model. Sman Teng Temple: RADAR data and digital elevation model. (Courtesy of R. G. Bloom, JPL-NASA.)



Remote Sensing in Archaeology, Figure 12 Photo shows the landscape below the Loughcrew passage tombs, County Meath, Ireland: relief-shaded LiDAR image of enclosures and field boundaries in "improved" pasture grassland subject to stone removal and periodic plowing. Note the better preservation of the earthworks in the legally protected unplowed area at *lower left*. (Courtesy of Dr. Colin A. Shell, Department of Archaeology, University of Cambridge, UK.)

represented by the use of helicopters as imaging platforms, allowing slower and lower flight paths, a multiple return feature (in which several reflections can be recorded from the same impulse, indicating, for example, tree canopies and ground as in Figure 13), combined with ultrahigh frequency, enabling much higher ground resolution. Densities of up to 60 pts/m^2 (about 10 cm resolution) can be obtained by these methods, allowing effective penetration of even the most densely vegetated areas and permitting the recording of micro-topographic variations even where the remains of archaeological features are severely degraded (Shaw and Corns, 2011).

Nevertheless, a degree of caution is needed. The production of a DTM using LiDAR technology is a complex process that involves several assumptions and decisions throughout the workflow of project preparation, data acquisition, and subsequent analysis. The archaeologist has to consider and understand the meaning of meta-information about the original point density, the time of flight, the instrumentation used, the type of aerial platform, the DTM-generation procedure, etc. (Doneus and Briese, 2011; Opitz and Cowley, 2013). If properly applied, the LiDAR technique could prove revolutionary in its impact on the process of archaeological mapping by making it possible to record previously hidden archaeological resources within woodland areas and (apparently) leveled landscapes. In favorable circumstances, it may even be possible to uncover whole "fossil" landscapes. This could have a dramatic impact on opportunities for archaeological and landscape conservation and management, as well as on scientific investigation of settlement dynamics in various phases of our history.



Remote Sensing in Archaeology, Figure 13 *Top*: conventional aerial photograph of Welshbury Hill Fort (UK) showing the dense tree canopy. (Image courtesy of the Forestry Commission, Source Cambridge University, Unit for Landscape Modelling (ULM), March 2004.) The dense woodland is not conducive to standard field survey, so it was felt that any technique that might better enable the recording of features in such woodland must be worth investigating further. The project used data flown by ULM and collected at a higher than average resolution allowing the creation of a 0.25 m grid. This was provided to staff at English Heritage as gridded files of both first and last pulse data together with an image file of the data once it had been processed using the vegetation removal algorithm. *Middle*: this image shows that the first pulse data simply recorded the canopy in much the same way as the standard aerial photograph: what is recorded is the top of the tree canopy. *Bottom*: the last pulse effectively removed the bulk of the tree cover revealing the features beneath. Last pulse data "removes" the trees revealing the ground surface. The remaining "trees" probably represent areas of particularly dense foliage or thick tree trunks/stumps. (LiDAR courtesy of the Forestry Commission, Source Cambridge University, Unit for Landscape Modelling (March 2004).)

Close-range aerial photography

From the end of nineteenth century, when Giacomo Boni used a balloon to take aerial photographs of the Foro Romano, to the present day, archaeologists have understood the desirability of acquiring low-altitude aerial imagery for purposes of documentation, conservation, and cultural resource management; the discovery of previously unidentified features plays only a minor role in this case. Various kinds of unmanned platforms have been used in archaeology and other scientific fields to lift the photographic camera so as to acquire large-scale imagery from relatively low heights (Figure 14).

Each of the methods noted below has its own distinct advantages and drawbacks (Verhoeven et al., 2009):

1. *Mats, poles, booms, and towers*. Although these platforms are cost effective, stable, and very easy to move, they are limited by their moderate maximum operational height of no more than about 20 m.
2. *Kites*. The use of kites in low-level aerial photography has been common since the 1970s, as these highly inexpensive and portable platforms can accommodate several kilograms of payload. Furthermore, the only thing that is needed for their effective operation is wind. This dependency, however, is also the method's main drawback: irregular winds are not suitable for kite-based photography, and the size of the kite is dependent upon the wind speed.
3. *Balloons and blimps*. These devices contrast with and complement kite photography in that they can be used in windless and very light wind conditions. Moreover, balloon photography is extremely flexible in its setup procedures, and operation is easy. However, balloons and blimps become difficult to position and to hold in windy conditions. Helium is also expensive and difficult or sometimes impossible to find in many countries. The gas containers, too, are heavy and unwieldy.
4. *Helikite*. This is a unique design, patented by Sandy Allsopp in 1993, and currently manufactured by Allsopp Helikites® Ltd. It combines a (small) helium-filled balloon with kite wings, securing the best properties of both platforms. The helium-filled balloon allows it to take off in windless weather conditions, whereas the kite components become important when there is wind, improving stability and providing the capacity to reach higher altitudes.
5. *Unmanned aerial vehicles (UAVs) or drones*. This category, which includes remote-controlled model aircraft and helicopters, generally involves high-end devices that allow very accurate control of the platform so as to produce photographic ortho-mosaics and, in the most advanced cases, photogrammetric stereo pairs (Eisenbeiss, 2009; Remondino and Campana, 2014). The use of such devices is growing in archaeology thanks to the improvement of photogrammetric software capable of producing accurate 3D models in a short time (Remondino, 2014b). There is also the possibility of equipping UAV platforms with a wide range of sensors, from thermal or infrared cameras to airborne LiDAR systems, video cameras, etc.

Ground truthing

Information collected from remotely sensed systems loses much of its potential meaning without detailed field survey on the ground. Effective ground truthing is often the key that unlocks the information content of remotely sensed data. Fieldwork represents the step in the process that aims to verify and enhance the results of a remote sensing study through comparison with independent evidence.

It is essential in this context to stress that the word "truthing" refers to the *interpretation* of remote sensing data; it does not imply that the actual data may be false (Hargrave, 2006). If remote sensing analysis is properly executed, the probability that interpreted features have some cultural or paleoenvironmental source is very high. The need for archaeologists to ground-check the features seen from the air has been a fundamental concept from the very origins of remote sensing (Poidebard, 1927; Crawford and Keiller, 1928). This step in the process is essential in order to define the interpretation keys and, hence, to develop or to advance the classification of anomalies into useful archaeological categories with differing levels of detail and interpretative precision, in a sequence such as:

1. Ditch, pit, wall, earthwork, etc.
2. Burial mound, grave, enclosure, settlement, etc.
3. Round barrow, long barrow, rectangular enclosure, Roman villa, etc.

The ground evaluation of anomalies can be done in a variety of ways. The conventional scheme uses a series of increasingly invasive and expensive techniques, removing some parts of the anomalies at each stage and consequently applying the more expansive and invasive techniques to a minority that have survived earlier stages of the screening process. The techniques used depend upon the conditions encountered at each site: land use, vegetation, material culture, conservation policies, etc. The basic sequence of this multistage approach might be summarized as follows:

1. *Visual inspection through field-walking survey*. Here, there is great value in the use of a mobile GIS device provided with a satellite navigation system (GPS) and up-to-date maps of the selected features for ground truthing. This guarantees the necessary accuracy to ensure the inspection of each anomaly. Common features, possibly recognizable during fieldwork, are localized depressions or ridges with regular shapes, differences in soil moisture, concentrations of gravel or apparently nonnative rock, archaeological artifacts, etc.
2. *Core sampling*. Ideally, cores should be taken from within the targeted anomaly as well as outside its apparent limits. Evidence could include the presence of charcoal, burned soil, bone, fragments of pottery,

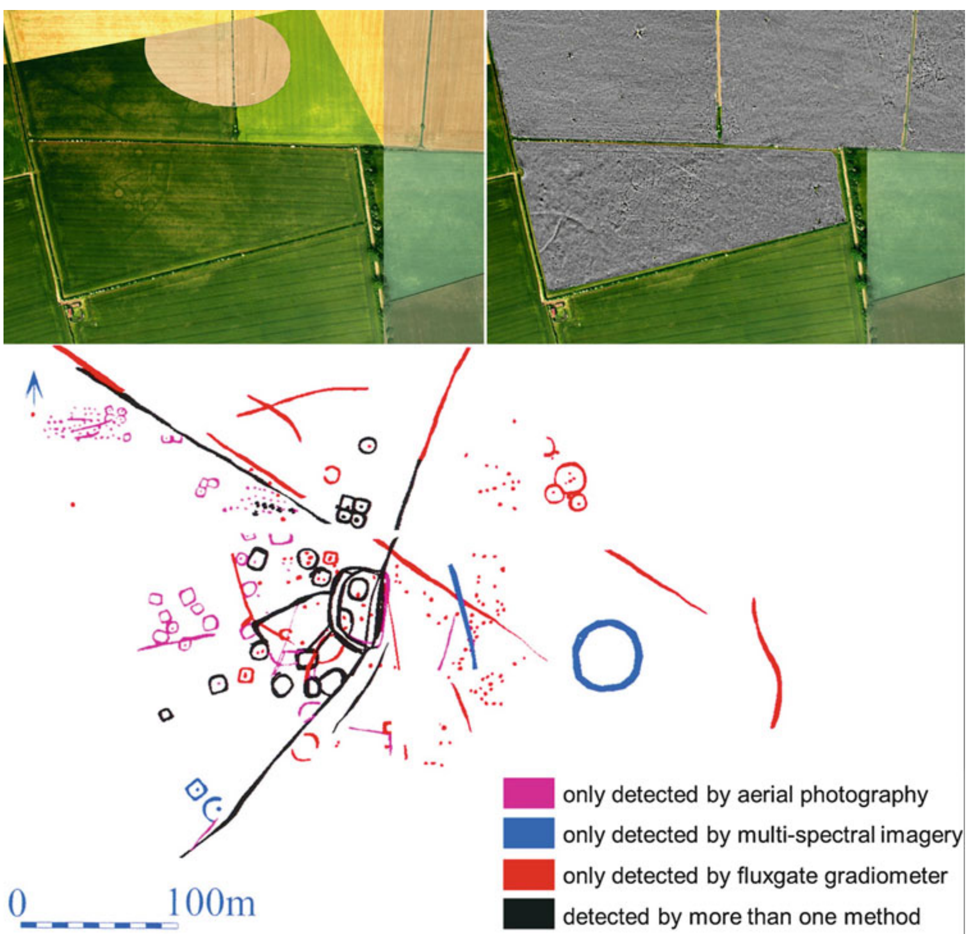
Remote Sensing in Archaeology, Figure 14 From *top* to *bottom* and from *left* to *right*. Ladder for documentation on archaeological excavation; watch tower aimed at the collection of photography, laser scanner data, etc.; giraffe photography uses a telescopic mast to elevate a high-quality digital SLR camera to heights generally between 5 up to10 m. This platform is used for collection of vertical photography and creation of a photomosaic of small areas at a very high level of detail; blimp of the University of Siena, Centre for GeoTechnologies, San Giovanni Val d'Arno; kite; helikite; balloon; from high-end UAV (unmanned aerial vehicle) systems to very low-cost UAV platforms. (Photos courtesy of the University of Siena, Laboratory of Landscape Archaeology and Remote Sensing (LAP&T) and Centre of GeoTechnologies (CGT), H. Eisenbeiss and F. Remondino.)

or other kinds of artifact. Often, one will not be able to determine whether a feature is present solely on the basis of such a soil core.

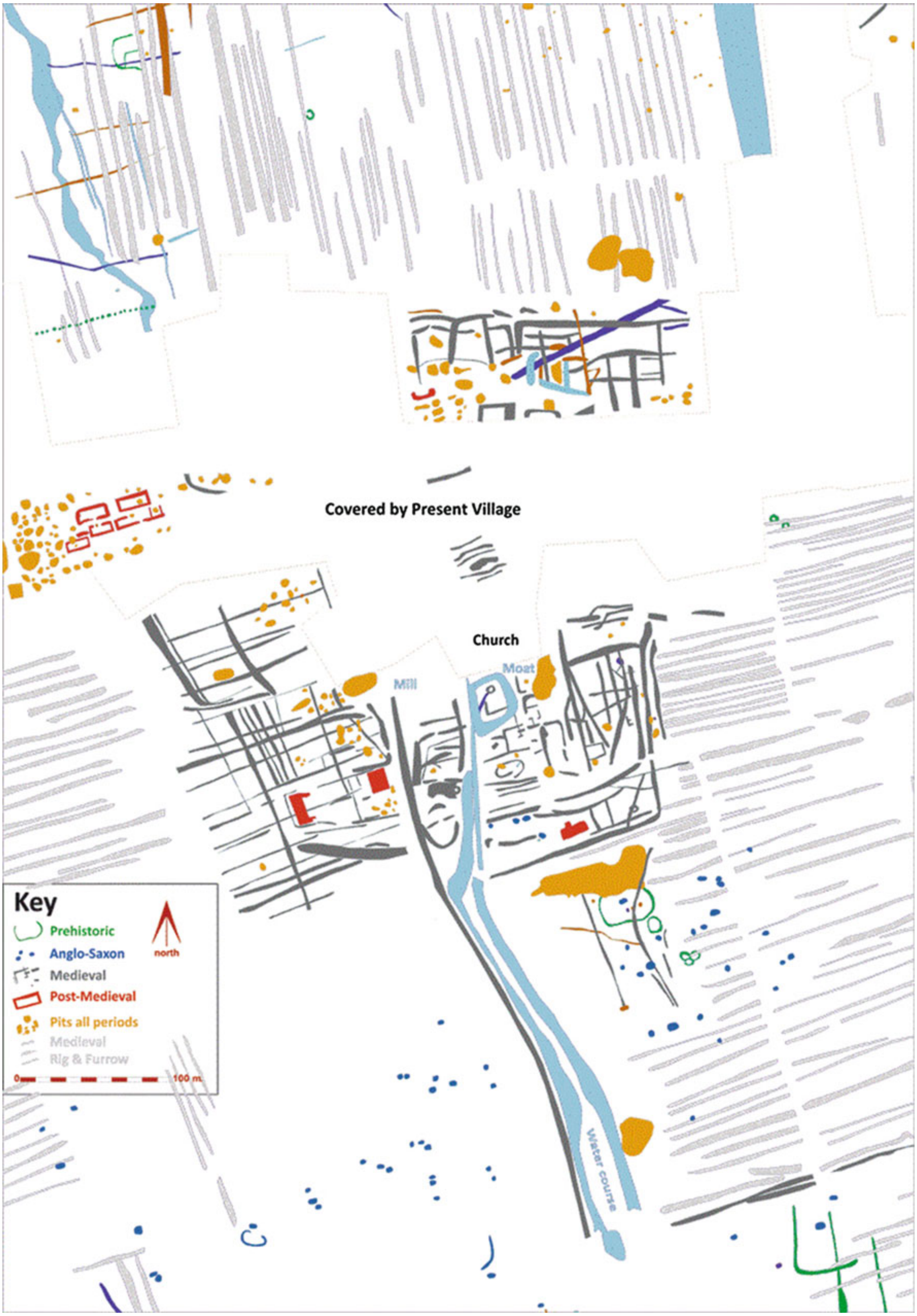
3. *Test pits or shovel test*. This is a common method, consisting of excavating small pits (generally measuring 1 m by 1 m) to the surface of sterile soil or to a depth of 70–120 cm (depending on the stability or instability of the sections). This makes it possible to note in the field any presence or variation in the concentration of artifacts or other cultural material. As with core sampling, the test pits should be excavated in pairs, one within and the other outside the anomaly. The main advantages of core sampling and test pits are their low cost and minimal invasiveness.
4. *Minimalist stratigraphic excavation*. Minimalist and well-planned stratigraphic excavation can be extremely efficient and reliable in verifying the presence of features in a way that is relatively noninvasive and cost effective. Unfortunately, this technique (as well as core sampling and test pitting) may not be possible in countries where social and political factors require ground truthing to be largely or wholly noninvasive.
5. *Mechanical excavation*. Perhaps the most convincing type of ground truthing is removal of the topsoil or plow-disturbed strata over large and contiguous areas. Subsurface features can then be marked, mapped, and wholly or partially excavated (Campana, 2011). This practice is mainly applied to verify the results of archaeological impact assessments in the case of infrastructure and other types of major construction work.

GIS data integration: mapping and interpretation

Lillesand and Kiefer, authors of one of the most authoritative manuals of remote sensing, maintain in their section on the basic concepts and founding principles of remote sensing as follows: "...successful application of remote sensing is premised on the integration of multiple, interrelated data sources and analysis procedures. No single combination of sensor and interpretation procedures is



Remote Sensing in Archaeology, Figure 15 Combining aerial campaigns with geophysical data shows that neither approach gives the same returns, confirming that identifying the archaeological capacity of the landscape requires the use of a multi-sensor approach; map of a site in West Heslerton (North Yorkshire, UK). (Courtesy of Dominic Powlesland, Landscape Research Centre.)



Remote Sensing in Archaeology, Figure 16 (Continued) appropriate to all resources inventorying and environmental monitoring applications" (Lillesand and Kiefer, 1994, 35). This is absolutely true for archaeological remote sensing (Powlesland, 2006).

A prerequisite for data integration of remotely sensed imagery is knowledge about each measurement's position in relation to a known system of geographical coordinates. Failure to satisfy this condition results in an inability to localize the acquired information. The entry of the data into a GIS is the basis for any attempt at integration of the information so as to develop a historical/archaeological narration or to ensure conservation of the archaeological resource. Georeferencing of the remotely sensed data does not represent the end of the archaeological mapping process, but only an intermediate stage. On their own, satellite imagery, aerial photographs, LiDAR imagery, and geophysical imagery signify little.

It is the responsibility of the archaeologist (often in collaboration with specialists) to give archaeological sense to the photographs or to the measurements of chemical and physical parameters in the soil. In summary, the interpretation of the data is made real and communicable through cartographic drawing of the elements perceived as anomalies (Palmer, 2000).

This is, therefore, the critical phase in landscape and archaeological research. In practice, the process advances through the drawing, digitally or by hand, of the anomalies and other elements deemed to be of archaeological interest. The georeferenced graphical restitution of the information contained in vertical or oblique aerial photographs, in high-resolution satellite imagery, in LiDAR data, and in maps derived from geophysical measurements makes it possible to overlay on topographic maps the results of the various investigative methods, along with a mass of other data that have been stratified layer upon layer over the years (Figure 15). The result is a jigsaw puzzle, a complex representation in which it is possible to measure and position each piece of information. At the same time, it is often possible to perceive the overall picture, whether single phase or spread across time, along with the overlapping and stratified fragments of whole systems of ancient and medieval landscapes. Through archaeological mapping and the use of GIS, it becomes possible to study these fragments together with other layers of archaeological and non-archaeological information in the writing of history, in heritage protection through the planning process, and through conservation or monitoring of the shared cultural inheritance (Figure 16; Campana, 2009).

Bibliography

Adams, R. E. W., 1980. Swamps, canals, and the location of ancient Maya cities. *Antiquity*, **54**(212), 206–214.

Aqdus, S. A., Drummond, J., and Hanson, W. S., 2008. Discovering archaeological cropmarks: a hyperspectral approach. In Chen, J., Jiang, J., and Maas, H.-G. (eds.), *XXIst Congress of the International Society for Photogrammetry and Remote Sensing, Technical Commission V, July 3–11, 2008, Beijing, China*. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XXXVII B5, pp. 361–365.

Avery, T. E., and Lyons, T. R., 1981. *Remote Sensing: Aerial and Terrestrial Photography for Archaeologists*. Washington, DC: Cultural Resources Management Division, National Park Service, U.S. Dept. of the Interior.

Barber, M., 2011. *A History of Aerial Photography and Archaeology: Mata Hari's Glass Eye and Other Stories*. Swindon: English Heritage.

Beck, A. R., 2011. Archaeological applications of multi/hyperspectral data – challenges and potential. In Cowley, D. C. (ed.), *Remote Sensing for Archaeological Heritage Management: Proceedings of the 11th EAC Heritage Management Symposium, Reykjavík, Iceland, 25–27 March 2010*. EAC Occasional Paper 5. Brussel: Europae Archaeologiae Consilium, pp. 87–97.

Bewley, R. H., 2002. Aerial survey: learning from a hundred years of experience? In Bewley, R. H., and Rączkowski, W. (eds.), *Aerial Archaeology: Developing Future Practice*. Amsterdam: IOS Press. NATO Science Series I, Life and Behavioural Sciences, Vol. 337, pp. 11–18.

Bewley, R. H., 2005. Aerial archaeology. The first century. In Bourgeois, J., and Meganck, M. (eds.), *Aerial Photography and Archaeology 2003: A Century of Information*. Ghent: Academia Press. Archaeological Reports Ghent University, Vol. 4, pp. 15–30.

Remote Sensing in Archaeology, Figure 16 A map of East Heslerton (North Yorkshire, UK) drawn by Dominic Powlesland demonstrates the integration of methodologies and data in the process of mapping evidence and understanding landscapes. While the surviving earthworks of the later medieval village show up well in English Heritage air photographs, geophysical surveys reveal much more detail of the medieval and later village, particularly in the areas beyond the present village to the north and west. To the west of the present village, the series of long rectangular enclosures with their short sides aligned to the present track coming down from the Wolds are termed crofts and tofts. The toft is where the house was built surrounded by a small garden area, and beyond it the croft was probably used for domestic food production. The land beyond the village was divided into "rig and furrow," the strip field system that dominated the medieval landscape of much of lowland England. The village was supplied with water from springs at the foot of the Wolds. To the south, the natural stream channel was managed from an early date with the water used to drive a mill and fill the moat associated with the Manor House. The site of the Manor is thought to have been largely destroyed when the present church, commissioned by Sir Tatton Sykes of Sledmere and designed by the celebrated Victorian architect G. E. Street, was built between 1873 and 1877. Street also designed the vicarage and had further buildings constructed to house the building team. The remains of a number of houses were demolished during the last century in the field immediately to the west of the village and to the south of the A64 trunk road, which cuts through the northern part of the medieval village. The evidence indicates that the village that survives today is considerably smaller than it had been in medieval times and, thus, is termed a shrunken village. (Map provided courtesy of D. Powlesland, Landscape Research Centre.)

Bewley, R. H., Crutchley, S. P., and Shell, C. A., 2005. New light on an ancient landscape: LiDAR survey in the Stonehenge World Heritage Site. *Antiquity*, **79**(305), 636–647.

Bloom, R. G., 1992. Space technology and the discovery of Ubar. *Point of Beginning*, **17**(2), 11–20.

Boni, G., 1900. *Fotografie e pianta altimetrica del Foro Romano*. Rome: Reale Accademia dei Lincei.

Bradford, J., 1957. *Ancient Landscapes: Studies in Field Archaeology*. London: Bell.

Campana, S., 2009. Archaeological site detection and mapping: some thoughts on differing scales of detail and archaeological 'non-visibility'. In Campana, S., and Piro, S. (eds.), *Seeing the Unseen: Geophysics and Landscape Archaeology*. London: Taylor & Francis, pp. 5–26.

Campana, S., 2011. 'Total archaeology' to reduce the need for rescue archaeology: the BREBEMI project (Italy). In Cowley, D. C. (ed.), *Remote Sensing for Archaeological Heritage Management: Proceedings of the 11th EAC Heritage Management Symposium, Reykjavík, Iceland, 25–27 March 2010*. EAC Occasional Paper 5. Brussel: Europae Archaeologiae Consilium, pp. 33–41.

Cavalli, R. M., Marino, C. M., and Pignatti, S., 2003. Hyperspectral airborne remote sensing as an aid to a better understanding and characterization of buried elements in different archaeological sites. In Forte, M., and Williams, P. R. (eds.), *The Reconstruction of Archaeological Landscapes through Digital Technologies: Proceedings of the 1st Italy-United States Workshop, Boston, Massachusetts, USA, November 1–3, 2001*. British Archaeological Reports, International Series 1151. Oxford: Archaeopress, pp. 29–32.

Comer, D. C., and Blom, G. R., 2007. Detection and identification of archaeological sites and features using synthetic aperture radar (SAR) data collected from airborne platforms. In Wiseman, J., and El-Baz, F. (eds.), *Remote Sensing in Archaeology*. New York: Springer, pp. 103–136.

Crawford, O. G. S., and Keiller, A., 1928. *Wessex from the Air*. Oxford: Clarendon Press.

Deuel, L., 1969. *Flights into Yesterday. The Story of Aerial Archaeology*. London: Macdonald.

Devereux, B. J., Amable, G. S., Crow, P., and Cliff, A. D., 2005. The potential of airborne lidar for detection of archaeological features under woodland canopies. *Antiquity*, **79**(305), 648–660.

Doneus, M., 2001. The impact of vertical photographs on analysis of archaeological landscapes. In Doneus, M., Eder-Hinterleitner, A., and Neubauer, N. (eds.), *Archaeological Prospection: 4th International Conference on Archaeological Prospection, Vienna, 19–23 September 2001*. Vienna: Austrian Academy of Sciences Press, pp. 94–96.

Doneus, M., and Briese, C., 2006. Full-waveform airborne laser scanning as a tool for archaeological reconnaissance. In Campana S., and Forte, M. (eds.), *From Space to Place. 2nd International Conference on Remote Sensing in Archaeology : Proceedings of the 2nd International Workshop, CNR, Rome, Italy, December 4–7, 2006*. British Archaeological Reports, International Series 1568. Oxford: Archaeopress, pp. 99–105.

Doneus, M., and Briese, C., 2011. Airborne laser scanning in forested areas – Potential and limitations of an archaeological prospection technique. In Cowley, D. C. (ed.), *Remote Sensing for Archaeological Heritage Management: Proceedings of the 11th EAC Heritage Management Symposium, Reykjavík, Iceland, 25–27 March 2010*. EAC Occasional Paper 5. Brussel: Europae Archaeologiae Consilium, pp. 59–76.

Doneus, M., Neubauer, W., Verhoeven, G., and Briese, C., 2011. Advancing archaeological airborne remote sensing: core concepts of the LBI-ArchPro initiative. In Drahor, M. G., and Berge, M. A. (eds.), *Archaeological Prospection: 9th International Conference on Archaeological Prospection, September 19–24, Izmir, Turkey*. Istanbul: Archaeology and Art Publications, pp. 12–15.

Donoghue, D. N. M., 2001. Multispectral remote sensing for archaeology. In Campana, S., and Forte, M. (eds.), *Remote Sensing in Archaeology: XI Ciclo di lezioni sulla ricerca applicata in archeologia, Certosa di Pontignano (Siena), 6–11 dicembre 1999*. Florence: All'Insegna del Giglio, pp. 181–192.

Donoghue, D. N. M., Beck, A., Galiatzatos, N., McManus, K., and Philip, G., 2006. The use of remote sensing data for visualising and interpreting archaeological landscapes. In Baltsavias, E., Gruen, A., Van Gool, L., and Pateraki, M. (eds.), *Recording, Modeling and Visualization of Cultural Heritage*. Leiden: Taylor and Francis, pp. 317–326.

Eisenbeiss, H., 2009. UAV photogrammetry. D.Sc. dissertation, University of Zürich. Zürich IGP Mitteilungen Nr.105. http://e-collection.library.ethz.ch/eserv/eth:498/eth-498-02.pdf#search=%22(author:henri eisenbeiss)%22.

Galiatsatos, N., 2014. Exploring archaeological landscapes with satellite imagery. In Remondino, F., and Campana, S. (eds.), *3D Recording and Modelling in Archaeology and Cultural Heritage: Theory and Best Practices*. Oxford: Archaeopress. British Archaeological Reports, International Series, Vol. 2598, pp. 89–100.

Going, J. C., 2002. A neglected asset. German aerial photography of the Second World War period. In Bewley, R. H., and Rączkowski, W. (eds.), *Aerial Archaeology: Developing Future Practice*. Amsterdam: IOS Press. NATO Science Series I, Life and Behavioural Sciences, Vol. 337, pp. 23–30.

Guaitoli, M. (ed.), 2003. *Lo sguardo di Icaro: Le collezioni dell'Aerofototeca nazionale per la conoscenza del territorio*. Roma: Campisano.

Hargrave, M. L., 2006. Ground truthing the results of geophysical survey. In Johnson, J. K. (ed.), *Remote Sensing in Archaeology: An Explicitly North American Perspective*. Tuscaloosa: The University of Alabama Press, pp. 269–304.

Holcomb, D. W., and Shingiray, I. L., 2007. Imaging radar in archaeological investigations: an image processing perspective. In Wiseman, J., and El-Baz, F. (eds.), *Remote Sensing in Archaeology*. New York: Springer, pp. 11–45.

Holden, N., Horne, P., and Bewley, R. H., 2002. High-resolution digital airborne mapping and archaeology. In Bewley, R. H., and Rączkowski, W. (eds.), *Aerial Archaeology: Developing Future Practice*. Amsterdam: IOS Press. NATO Science Series I, Life and Behavioural Sciences, Vol. 337, pp. 173–180.

Horne, P., 2011. The english heritage national mapping programme. In Cowley, D. C. (ed.), *Remote Sensing for Archaeological Heritage Management: Proceedings of the 11th EAC Heritage Management Symposium, Reykjavík, Iceland, 25–27 March 2010*. EAC Occasional Paper 5. Brussel: Europae Archaeologiae Consilium, pp. 143–151.

Jones, R. J. A., and Evans, R., 1975. Soil and crop marks in the recognition of archaeological sites by air photography. In Wilson, D. R. (ed.), *Aerial Reconnaissance for Archaeology*. London: Council for British Archaeology. Research reports, Council for British Archaeology, Vol. 12, pp. 1–11.

Khawaga, M., 1979. A contribution to fractal pattern of the Abu Tartar plateau, Western Desert, Egypt. *Annals of the Geological Survey of Egypt*, **9**, 163–171.

Lasaponara, R., and Masini, N., 2012. *Satellite Remote Sensing. A New Tool for Archaeology*. Dordrecht: Springer. Remote Sensing and Digital Image Processing, Vol. 16.

Lillesand, T. M., and Kiefer, R. W., 1994. *Remote Sensing and Image Interpretation*, 3rd edn. New York: Wiley.

Lyons, T. R., and Avery, T. E., 1977. *Remote Sensing: A Handbook for Archaeologists and Cultural Resources Managers*. Washington, DC: Cultural Resources Management Division, National

Park Service, U.S. Dept. of the Interior. Contribution of the Chaco Center, Vol. 4.

Lyons, T. R., and Mathien, F. J., 1980. *Cultural Resources Remote Sensing*. Washington, DC: Cultural Resources Management Division, National Park Service.

McCauley, J. F., Schaber, G. G., Breed, C. S., Grolier, M. J., Haynes, C. V., Issawi, B., Elachi, C., and Blom, R., 1982. Subsurface valleys and geoarcheology of the eastern Sahara revealed by shuttle radar. *Science*, **218**(4576), 1004–1020.

McHugh, W. P., Schaber, G. G., Breed, C. S., and McCauley, J. F., 1989. Neolithic adaptation and the Holocene functioning of the Tertiary palaeodrainages in southern Egypt and northern Sudan. *Antiquity*, **63**(239), 320–336.

Moore, E., Freeman, T., and Hensley, S., 2007. Spaceborne and airborne radar at Angkor: introducing new technology to the ancient site. In Wiseman, J., and El-Baz, F. (eds.), *Remote Sensing in Archaeology*. New York: Springer, pp. 185–216.

Musá, A. H., Dolphin, L. T., and Mukhtar, M. J., 1977. *Applications of Modern Sensing Techniques to Egyptology*. Menlo Park, CA: SRI International.

Musson, C., 1994. *Wales from the Air: Patterns of Past and Present*. Aberystwyth: Royal Commission on the Ancient and Historical Monuments of Wales.

Opitz, R. S., and Cowley, D. C., 2013. *Interpreting Archaeological Topography. Airborne Laser Scanning, 3D Data and Ground Observation*. Oxford: Oxbow Books.

Palmer, R., 2000. A view from above: can computers help aerial survey? In Lock, G. R., and Brown, K. (eds.), *On the Theory and Practice of Archaeological Computing*. Oxford: Oxford University Committee for Archaeology. Oxford University Committee for Archaeology, Monograph, Vol. 51, pp. 107–131.

Palmer, R., 2007. Seventy-five years v. ninety minutes: implications of the 1996 Bedfordshire vertical aerial survey on our perceptions of clayland archaeology. In Mills, J., and Palmer, R. (eds.), *Populating Clay Landscapes*. Tempus: Stroud, pp. 88–103.

Parcak, S. H., 2009. *Satellite Remote Sensing for Archaeology*. New York: Routledge.

Piccarreta, F., and Ceraudo, G., 2000. *Manuale di aerofotografia archeologica. Metodologia, tecniche e applicazioni*. Bari: Edipuglia.

Poidebard, A., 1927. Les routes anciennes en Haute-Djézireh. *Syria*, **8**, 55–65.

Pope, K. O., and Dahlin, B. H., 1989. Ancient Maya wetland agriculture: new insights from ecological and remote sensing research. *Journal of Field Archaeology*, **16**(1), 87–106.

Powlesland, D., 2006. Redefining past landscapes: 30 years of remote sensing in the Vale of Pickering. In Campana S., and Forte, M. (eds.), *From Space to Place. 2nd International Conference on Remote Sensing in Archaeology : Proceedings of the 2nd International Workshop, CNR, Rome, Italy, December 4–7, 2006*. British Archaeological Reports, International Series 1568. Oxford: Archaeopress, pp. 197–201.

Powlesland, D., 2010. Identifying mapping and managing the unmanageable: the implication of long term multi-sensor research into the archaeology of the Vale of Pickering. Yorkshire, England. In Forte, M., Campana, S., and Liuzza, C. (eds.), *Space, Time, Place: Third International Conference on Remote Sensing in Archaeology, 17th–21st August 2009, Tiruchirappalli, Tamil, Nadu, India*. British Archaeological Reports, International Series 2118. Oxford: Archaeopress, pp. 9–16.

Powlesland, D., and Donoghue, D. N. M., 1993. A multi-sensory approach to mapping the prehistoric landscape. In *Proceedings of the 9th Natural Environment Research Council Airborne Symposium*. Swindon, UK: NERC, pp. 88–96.

Rączkowski, W., 2001. Science and/or art: aerial photographs in archaeological discourse. *Archaeologia Polona*, **39**, 127–146.

Rączkowski, W., 2005. To overcome infirmity. Current approaches to aerial archaeology in Poland. In Bourgeois, J., and Meganck, M. (eds.), *Aerial Photography and Archaeology 2003: A Century of Information*. Ghent: Academia Press. Archaeological Reports Ghent University, Vol. 4, pp. 121–135.

Remondino, F., 2011. 3D recording for cultural heritage. In Cowley, D. C. (ed.), *Remote Sensing for Archaeological Heritage Management. Proceedings of the 11th EAC Heritage Management Symposium, Reykjavík, Iceland, 25–27 March 2010*. Europae Archaeologia Consilium Occasional Paper No. 5. Brussels: EAC, pp.107–115.

Remondino, F., 2014a. Photogrammetry: theory. In Remondino, F., and Campana, S. (eds.), *3D Recording and Modelling in Archaeology and Cultural Heritage Theory and Best Practices*. Oxford: Archaeopress. British Archaeological Reports, International Series, Vol. 2598, pp. 65–73.

Remondino, F., 2014b. UAV: Platforms, regulations, data acquisition and processing. In Remondino, F., and Campana, S. (eds.), *3D Recording and Modelling in Archaeology and Cultural Heritage: Theory and Best Practices*. Oxford: BAR International Series, Vol. 2598, pp. 74–87.

Remondino, F., and Campana, S. (eds.), 2014. *3D Recording and Modelling in Archaeology and Cultural Heritage: Theory and Best Practices*. Oxford: Archaeopress. British Archaeological Reports, International Series, Vol. 2598.

Risbøl, O., Gjertsen, A. K., and Skare, K., 2006. Airborne laser scanner of cultural remains in forest: some preliminary results from Norwegian project. In Campana S., and Forte, M. (eds.), *From Space to Place. 2nd International Conference on Remote Sensing in Archaeology : Proceedings of the 2nd International Workshop, CNR, Rome, Italy, December 4–7, 2006*. British Archaeological Reports, International Series 1568. Oxford: Archaeopress, pp. 107–112.

Schaber, G. G., and Gumerman, G. J., 1969. Infrared scanning images: an archaeological application. *Science*, **164**(3880), 712–713.

Sever, T. L., 1998. Validating prehistoric and current social phenomena upon the landscape of the Peten, Guatemala. In Liverman, D. M., Moran, E. F., Rindfuss, R. R., and Stern, P. C. (eds.), *People and Pixels: Linking Remote Sensing and Social Science*. Washington, DC: National Academy Press, pp. 145–163.

Shaw, R., and Corns, A., 2011. High resolution LiDAR specifically for archaeology: are we fully exploiting this valuable resource? In Cowley, D. C. (ed.), *Remote Sensing for Archaeological Heritage Management: Proceedings of the 11th EAC Heritage Management Symposium, Reykjavík, Iceland, 25–27 March 2010*. EAC Occasional Paper 5. Brussel: Europae Archaeologiae Consilium, pp. 77–86.

Sheets, P., and Sever, T. L., 1991. Prehistoric footpaths in Costa Rica: transportation and communication in a tropical rainforest. In Trombold, C. D. (ed.), *Ancient Road Networks and Settlement Hierarchies in the New World*. Cambridge: Cambridge University Press, pp. 53–65.

Shell, C. A., 2002. Airborne high-resolution digital, visible, infrared and thermal sensing for archaeology. In Bewley, R. H., and Rączkowski, W. (eds.), *Aerial Archaeology: Developing Future Practice*. Amsterdam: IOS Press. NATO Science Series I, Life and Behavioural Sciences, Vol. 337, pp. 181–195.

Shell, C. A., 2005. Digital airborne remote sensing: high-resolution digital airborne survey for archaeological research and cultural

landscape management. In Musson, C., Palmer, R., and Campana, S. (eds.), *Volo nel Passato: Aerofotografia e cartografia archeologica*. Florence: All'Insegna del Giglio, pp. 271–283.
Shennan, I., and Donoghue, D. N. M., 1992. Remote sensing in archaeological research. In Pollard, A. M. (ed.), *New Development in Archaeological Science: A Joint Symposium of the Royal Society and the British Academy February 1991*. Proceedings of the British Academy 77. Oxford: Oxford University Press, pp. 223–232.
Sittler, B., and Schellberg, S., 2006. The potential of LIDAR in assessing elements of cultural heritage hidden under forest or overgrown by vegetation: possibilities and limits in detecting microrelief structures for archaeological surveys. In Campana S., and Forte, M. (eds.), *From Space to Place. 2nd International Conference on Remote Sensing in Archaeology : Proceedings of the 2nd International Workshop, CNR, Rome, Italy, December 4–7, 2006*. British Archaeological Reports, International Series 1568. Oxford: Archaeopress, pp. 117–122.
Stolze, F., 1882. *Persepolis; Die achaemenidischen und sasanidischen Denkmäler und Inschriften von Persepolis, Istakhr, Pasargadae, Shâkpûr*. Berlin: Ahser.
Traviglia, A., 2007. MIVIS hyperspectral sensors for the detection and GIS supported interpretation of subsoil archaeological sites: An Italian case study. In Clark, J. T., and Hagemeister, E. M. (eds.), *Digital Discovery: Exploring New Frontiers in Human Heritage. CAA 2006. Computer Applications and Quantitative Methods in Archaeology. Proceedings of the 34th Conference, Fargo, United States, April 2006*. Budapest: Archaeolingua, pp. 287–299.
Verhoeven, G. J. J., Loenders, J., Vermeulen, F., and Docter, R., 2009. Helikite aerial photography – a versatile means of unmanned, radio controlled, low-altitude aerial archaeology. *Archaeological Prospection*, **16**(2), 125–138.
Weishampel, J. F., Chase, A. F., Chase, D. Z., Drake, J. B., Shrestha, R. L., Slatton, K. C., Awe, J. J., Hightower, J., and Angelo, J., 2010. Remote sensing of ancient Maya land use features at Caracol, Belize related to tropical rainforest structure. In Forte, M., Campana, S., and Liuzza, C. (eds.), *Space, Time, Place: Third International Conference on Remote Sensing in Archaeology, 17th–21st August 2009, Tiruchirappalli, Tamil, Nadu, India*. British Archaeological Reports, International Series 2118. Oxford: Archaeopress, pp. 45–52.
Wilson, D. R., 2000. *Air Photo Interpretation for Archaeologists*, 2nd edn. Stroud: Tempus.
Wiseman, J., and El-Baz, F., 2007. *Remote Sensing in Archaeology.* New York: Springer.

WEB References

Aerial Archaeology Research Group. http://www.univie.ac.at/aarg.
International Society for Archaeological Prospection. http://www.brad.ac.uk/archsci/archprospection/.

Cross-references

Electrical Resistivity and Electromagnetism
Field Survey
Geographical Information Systems (GIS)
Geomorphology
Geophysics
Ground-penetrating Radar
Landscape Archaeology
Magnetometry for Archaeology

ROCKSHELTER SETTINGS

Susan M. Mentzer
Institute for Archaeological Sciences, University of Tübingen, Germany
School of Anthropology, University of Arizona, Tucson, AZ, USA

Synonyms

English: *cove*; *hole*; *hollow*; *rock shelter*; *rockhouse*; *rock-shelter*; *shelter*
French: *abri*, *abri sous roche*, *grotte*
Spanish: *abrigo roscoso*, *cova*, *cueva*
German: *Felsdachshutz*, *Höhle*
Italian: *riparo*, *grotta*
Arabic: *ghar*

Definition

Rockshelter. A natural cavity enclosed by one or more rock walls and an overhang that provides protection from the elements (wind, precipitation, sun, or a combination thereof).

Introduction

Rockshelters are important settings for archaeological sites because they form in numerous ways and in a variety of bedrock types and landscapes. The same properties of rockshelters that provide protection to their human and animal inhabitants also contribute to the protection and preservation of archaeological deposits left within them.

Humans exploit rockshelters for a variety of reasons. Ethnographic studies have revealed many different human behaviors and spatial patterning of material remains within these sites. For example, Binford (1996) notes that ethnographic uses of rockshelters tend to emphasize transient needs or short-term exploitation over long-term habitation. These transient functions can include use as refuges and hiding places; caches and storage; sources of food, water, and material resources; and ritual localities. In sites that are used for habitation, both Binford (1996) and Galanidou (2000) describe a "modular pattern" of use, which includes arrangement of activities, demarcation of areas for different families, construction of depressions and hearths, use of space for sleeping purposes, patterned discard of waste, and movement of large rocks. Finally, as documented in an ethnogeoarchaeological study by Brochier et al. (1992), humans extend the desirable properties of rockshelters to other species and utilize these natural spaces as stables or byres for domestic herbivores.

The geoarchaeology and sedimentology of rockshelters are frequently classified with that of caves (e.g., Collcutt, 1979; Butzer, 1981; Farrand, 1985; Funk, 1989; Straus, 1990; Farrand, 2001; Woodward and Goldberg, 2001).

In site distribution and settlement pattern studies, rockshelters are also generally grouped with caves, rather than with open-air localities. In fact, the terms "cave" and "rockshelter" are sometimes used interchangeably when naming sites (e.g., Sibudu Cave, which is actually a large shelter; Goldberg et al., 2009), either as a consequence of local naming conventions or due to the fact that the site morphology changed over time. Indeed, some types of rockshelter are created as a result of the collapse of larger cave systems, and in some geomorphic settings, caves and rockshelters may be clustered together. Davis (1990, 332), coming from a North American perspective, defines three types of caves: "caverns," which are formed overwhelmingly in calcareous or volcanic bedrock and have portions that are not lit by the sun; "traps," which are also predominantly calcareous or volcanic and are vertical in morphology with no outlets; and "rockshelters," which are for the most part lit by sunlight and also provide some form of shelter for organisms. Other researchers consider caves to be deeper than they are wide and rockshelters to be wider than they are deep (Miller, personal communication).

In the archaeological literature more broadly, rockshelters and caves differ in several ways. Caves are subterranean systems containing areas that are, to some degree, permanently dark. Rockshelters are cavities that are always lit by direct or indirect sunlight. Additionally, not all caves contain natural conduits to the Earth's surface. In contrast, active rockshelters are surface features that can be accessed from the surrounding landscape. Although most caves form through karstic processes, some, such as lava tubes, do not. Compared to rockshelters, cave formation processes are limited in variability.

Rockshelters are extremely diverse features that exhibit myriad forms. As outlined below, rockshelters are created in igneous, metamorphic, and sedimentary bedrock, as well as in semi-consolidated sediments. Rockshelters occur in coastal marine, lacustrine, glacial, eolian, and interior orogenic settings, and they exist in all latitudes and environmental regimes. Due to the high variability in their formation processes, rockshelters are impacted by different depositional and erosional processes, and they are more abundant than caves. Hence, archaeological sites located in rockshelters are also more abundant than true cave sites.

On the other hand, the entrance portions of caves that humans typically utilize most heavily (Butzer, 1971) share many features in common with rockshelters:

1. They provide protection from the elements (e.g., precipitation, wind, sun) and have unique internal environments that are generally warmer in winter and cooler in summer compared to open-air sites (Straus, 1990).
2. They are within the zone illuminated by sunlight.
3. They can be populated by plants of various types.
4. They frequently open onto broad spaces that can be occupied or utilized in different ways.

Although cave systems may be physically bigger than most rockshelters, they may be comparable in terms of usable occupation space.

Because rockshelters are not geomorphic features in the strictest sense – in that they are classified as such based on their morphological suitability for human or animal occupation rather than their formation processes – the identification of an archaeological site as being situated within a rockshelter is colloquial rather than formalized. Rockshelters are also transient features (Straus, 1990; Farrand, 2001). The life history of a rockshelter is determined by its host bedrock type and the rate of erosional processes. Despite their transient nature over geological timescales, rockshelters can be highly visible on the landscape, and thus their sedimentary sequences are impacted by the effects of repeated human and animal visits over much longer periods of time relative to open-air sites (Barton and Clark, 1993). A clear understanding of the variations in geologic settings and rates of formation processes of rockshelters is therefore very important for effective incorporation of rockshelters into local and regional studies of landscape use, site distribution, and human mobility patterns.

Currently, the geoarchaeological literature lacks a formal classification system for rockshelter sites. Heydari (2007) proposed a classification system for shelters found in the Zagros Mountains of Iran; however, his system is specific to inland karstic limestone regimes in arid environments. Other classifications, such as the boulder shelter system outlined by Mercader et al. (2003), are specific to other regions or geologic settings. The lack of a global organization system has resulted in haphazard descriptions of shelter morphology and formation processes in archaeological site reports, and this has limited the development of a standardized protocol for rockshelter sedimentological analyses.

This entry provides the foundation for a comprehensive organizational system and outlines the range of approaches to the geoarchaeological study of rockshelter sites. First, an expanded classification system describes shelters formed in sedimentary, igneous, and metamorphic bedrock types, as well as within terrestrial deposits. Second, sedimentological issues are presented, indicating that rockshelters contain sediments of geogenic, biogenic, and anthropogenic origin that may be deposited as a result of human or animal activities or natural processes. Third, rockshelter sediments are also subject to geological, biological, and human-induced post-depositional modifications, both mechanical and chemical. Finally, appropriate analytical strategies by geoarchaeologists working on the sediments of rockshelter sites depend upon a complete understanding of all possible sources of sediment and rockshelter life histories.

Rockshelter formation processes

A global rockshelter classification system is outlined in Table 1. Rockshelters can be divided into two main

Rockshelter Settings, Table 1 A rockshelter classification system organized by primary formation process. A number of secondary processes (e.g., salt and frost spalling, tectonic movements, human activity) may contribute to morphological changes during shelter formation histories

Rockshelter type	Cavity type	Formation regime	Primary process	Bedrock	Geomorphic features
Lava shelters	Primary	Subsurface	Lava flow dynamics	Basalt and andesite	Collapsed lava tubes, inflationary caves, liftup caves, blisters
Karstic rockshelters	Secondary	Subsurface	Chemical (phreatic and meteoric) dissolution, combined with mass movement that contributes to collapse or breach of cavities	Calcareous rock, including limestone, dolomite, marble, travertine, and tufa	Karst rockshelters, collapsed caves, collapsed dolines, footcaves
Etchform shelters	Secondary	Subsurface	Etchplanation	Coarse crystalline and coarse clastic rock	Cliff face cavities, boulder piles
Scarp foot and surface karst shelters	Secondary	Near surface	Sapping, scarp-foot weathering, chemical dissolution, biological activity	Any	Basal notches, flares, solution hollows, swamp slots, footcaves, flared boulders, mushroom rocks, haystacks, cliff face cavities, theater heads, overhangs
Tafoni and spall shelters	Secondary	Surface	Salt weathering and spalling, hydration weathering, frost spalling, biological activity	Coarse crystalline and coarse clastic rock	Hollows, arches, visors, tortoiseshell rocks, alcoves, cliff face cavities, boulder piles
Abrasion and entrainment shelters	Secondary	Surface	Differential weathering as a result of scouring by particles entrained in a fluid (wave abrasion, fluvial abrasion, glacial abrasion, eolian winnowing); deposition of entrained materials as flood boulders and glacial erratics	Any, although common in sedimentary and metamorphosed sedimentary rocks	Overhangs, cornices and horizontal cavities in sedimentary rocks with horizontal or mildly dipping bedding sequences; vertical or arched cavities in faults, folds, and jointed rocks; horizontal cavities near former glacier, lake, river, or sea levels; yardangs, wind eddy hollows; flood boulders, glacial erratics, and till piles
Tectonic shelters	Secondary	Surface	Faulting, collapse of fault breccia, earthquakes	Any	Fault scarps, cliff face cavities, boulder piles
Pseudokarstic shelters	Secondary	Surface	Differential weathering, undercutting, piping	Semi-consolidated sedimentary surface deposits, marl, tuff, tufa, travertine, fine-grained intrusive dikes and sills	Pseudokarst, loess karst

groups: those that occupy primary cavities and those that occupy secondary cavities. The latter grouping includes cavities that form as a result of subsurface and surface weathering processes. Despite these broad groupings, most shelters form as a result of a combination of primary and secondary processes. For example, karstic shelters may be further modified by ceiling collapse due to frost spalling or tectonic activity. In addition, human activities can contribute to weathering as secondary processes. For example, the construction of fires within shelters can induce or contribute to thermoclastic weathering of bedrock (Kourampas et al., 2009). Abrasive rubbing of shelter walls by people and livestock has been observed in ethnographic contexts (Brochier et al., 1992; Ward et al., 2006), and some bedrock types and their inclusions may be quarried for lithic raw materials, pigment manufacture, or construction purposes (see Figure 1d). These behaviors may contribute to both sedimentation and morphological modification of some sites.

Primary cavities result from bedrock formation processes and are limited to mafic igneous bedrock types. Types of primary cavities that can form rockshelters include lava tubes, inflationary caves, and liftup caves. Lava tubes form in one of two ways, and both formation processes yield long, hollow cavities within a basalt bedrock. In one way, molten lava flows within cooler portions of a pahoehoe-type basalt (lava with low viscosity and smooth flow patterns). After the lava exits, a long, sinuous tube is left beneath the surface of the basalt flow. In the second way, a channel of lava hardens from the exterior inward. Emptying of the center of the channel yields a tube. Collapse of the roof or lateral erosion of the basalt flow may expose a portion of the tube, producing either a cave or a rockshelter, depending on the cavity morphology. Inflationary and blister caves (Figure 1) form when gas bubbles or areas of high pressure build within a lava flow. Collapse of one or more of the walls of the bubble following the cooling of the rock can result in the formation of a cavity, with later erosion exposing a shelter. Liftup caves form in a similar manner, but they are located along the edge of a flow, resulting in one or more horizontal cavities along its perimeter. Erosion of these features, as with lava tubes, can lead to the exposure of small cavities or shelters. An example of an archaeological site located in a lava shelter is the Upper Paleolithic site of Aghitu-3 in Armenia (see Figure 1b). Because lava tube shelters, inflationary caves, and liftup caves form only in basalt and rarely in andesite (more viscous lava richer in silica), their worldwide distribution is limited to active and relict volcanic provinces.

Secondary cavity rockshelters form within rocks during subsurface or surface weathering processes. Subsurface or subaerial weathering processes that can lead to the formation of rockshelters include solution karst and etchplanation.

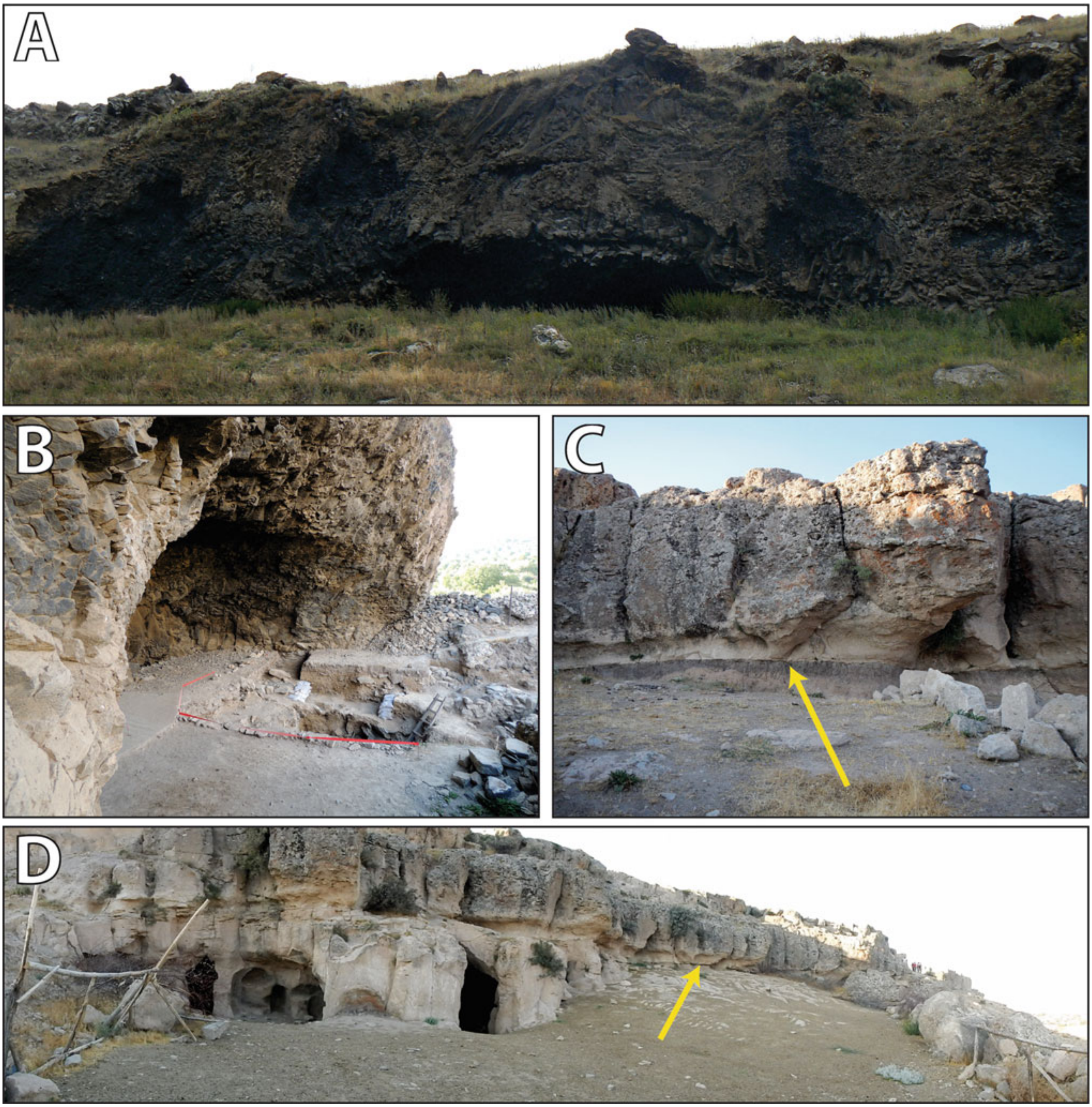
Solution karst forms in calcareous bedrock of sedimentary or metamorphic origin (e.g., limestone, dolomite, and marble) due to chemical weathering by acidic groundwater (Ford and Williams, 2007). Solution karst may form at considerable depth within the bedrock, but karstic systems are exploited by people only when non-karstic surface weathering processes, such as cliff face retreat, breach subterranean chambers to form accessible caves. Rockshelters form when exposed caves collapse further (Figure 2a). Because a single system may be breached in several places, caves and rockshelters of various shapes and sizes may be clustered on the landscape. An example of a cave and rockshelter cluster containing archaeological sites is the Middle and Upper Paleolithic Hohlenstein Stadel complex in the Lone Valley of Germany (Figure 2b). Rockshelters and caves may also form when surface karst processes breach subterranean systems (Sweeting, 1973). As an example, collapse dolines, also known as sinkholes, may be bounded by cave and rockshelter systems that may be accessed from above. Karstic shelters are found in areas with calcareous bedrock, but are most common in middle latitudes. Thus, they are present on every continent except Antarctica but have limited distribution in South America and most parts of Africa.

Etchplanation is another type of subsurface weathering that can produce natural cavities in bedrock, as well as boulder piles that provide sheltered areas (Twidale and Vidal Romani, 2005). Etchplanation occurs most commonly in jointed or faulted granitic and gneissic bedrocks that are buried by sedimentary deposits or surrounded by more highly weatherable bedrock types. Etchplanation occurs in two phases: subsurface weathering followed by exhumation. During the subsurface weathering phase, water percolation along joints and faults causes the alteration of micas and feldspars, transforming them into clay. During the exhumation phase, the overlying sedimentary deposits, as well as the weathered clays, are removed by water or wind. The resulting geomorphic features include boulder piles, domes, inselbergs, kopjes, and tors. Spaces between and beneath boulders form cavities and provide shelter from the elements. Examples of archaeological boulder pile shelters that formed as a result of etchplanation include the Ituri Rock Shelters in the Congo (Mercader et al., 2003). Hollows and overhangs are also present within domes, inselbergs, kopjes, and tors, where they form from over-widened joints or partial collapse of the bedrock. The Middle Stone Age site of Diepkloof Rock Shelter in South Africa formed in this manner when a large sandstone boulder, undermined by differential subsurface weathering of a shale layer, detached from the cliff face, leaving a cavity and overhang in a kopje (Miller et al., 2013) (Figure 3a). Etchform shelters are most commonly found in Paleozoic shield complexes in the humid subtropics where annual temperatures and precipitation are high. Elsewhere, these features may be considered relicts of periods in Earth's history when average temperatures were warmer or when now arid areas previously received higher precipitation.

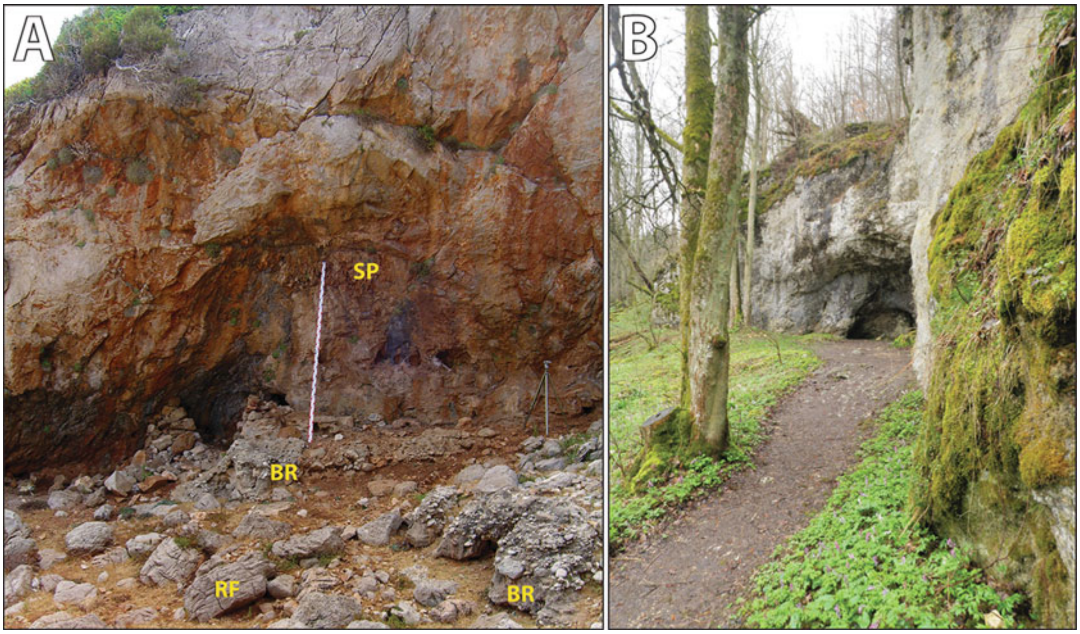
Scarp-foot weathering and sapping are near-surface weathering processes that operate in the same manner as etchplanation and karst, but at considerably shallower depths and in a wider range of bedrock types and climatic regimes. Scarp-foot weathering occurs at the bases of cliffs or large boulder edges. At these locations, increased moisture, sometimes combined with the activities of plants and other organisms, leads to increased chemical dissolution of carbonate bedrock (surface karst) or alteration of crystalline rocks (McDonald and Twidale, 2011). As in etchplanation, a later phase of deflation may expose the weathered area, producing concavities or notches at the base of the cliff. These features may also be termed solution hollows and flares. When large boulders are weathered in this manner, they may be termed flared boulders, mushrooms, or haystacks. Archaeological examples include the site located in a basal notch illustrated in Figure 3c, and Akrotiri *Aetokremnos*.

Surface weathering processes produce rockshelters in nearly any type of rock or terrestrial sedimentary deposit. The four main groups of shelters that form as a result of surface weathering processes are (1) tafoni and spall shelters, (2) abrasion and entrainment shelters, (3) tectonic shelters, and (4) pseudokarstic shelters.

Tafoni (Figure 4) are surface features of highly variable shape and size that form frequently in arid environments or coastal settings as a result of salt weathering, sometimes in combination with biological activity, frost spalling, thermal shock or insolation weathering, hydration weathering, and abrasion. These processes can operate at a variety of scales. Hydration weathering, salt weathering, and frost spalling can impact individual mineral grains, with chemical weathering of nearby mineral grains to swelling clays, precipitation of salt crystals from



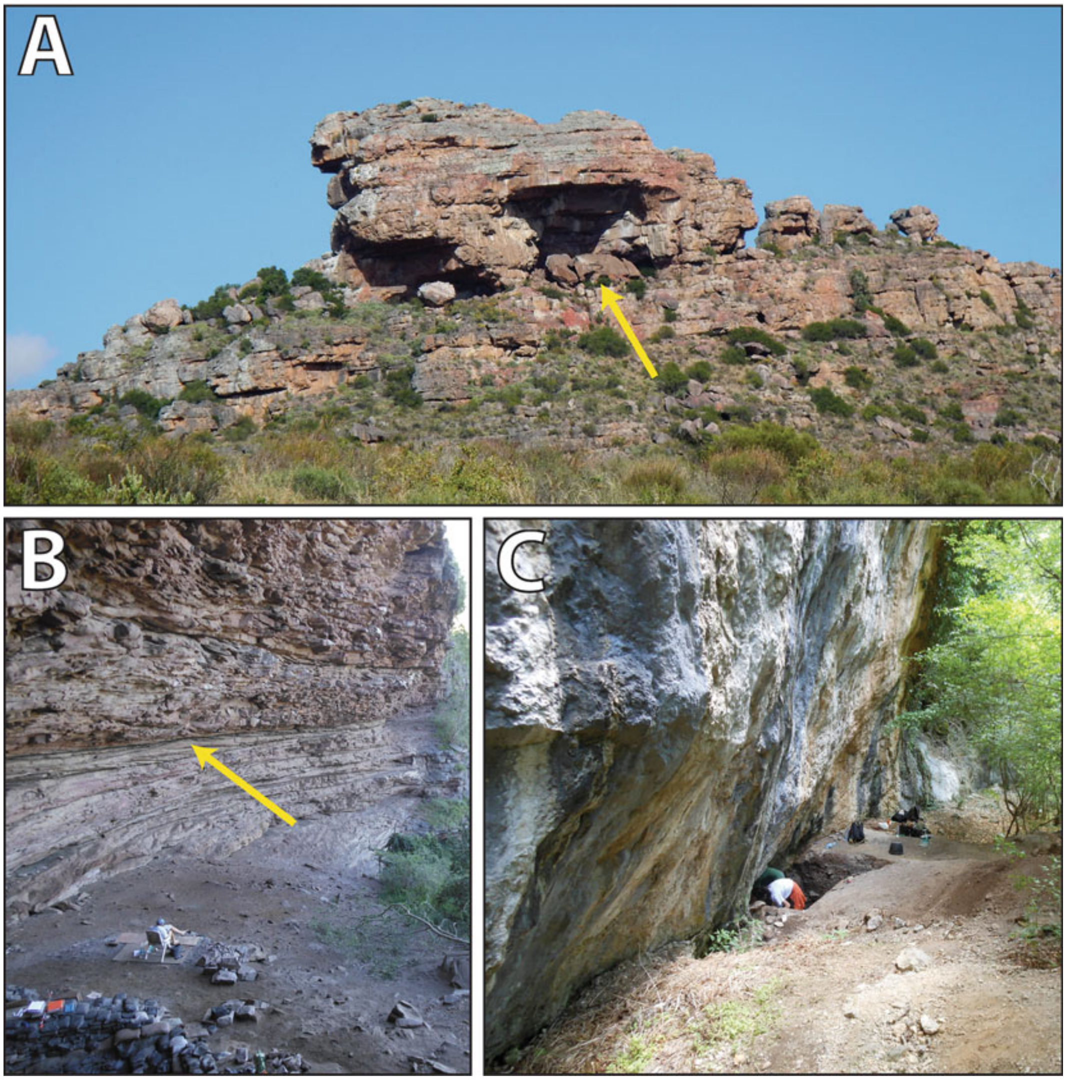
Rockshelter Settings, Figure 1 Shelters formed in extrusive volcanic rocks or lava shelters. (**a**) Inflationary caves and blister shelters are present at the edge of a basaltic lava flow. Erosion along the face of the lava flow has exposed internal primary cavities formed by gases that were trapped within the lava as it cooled. Sisian Caves, Armenia (Photo credit: Andrew W. Kandel). (**b**) Close-up view of a blister shelter in basalt. Collapse of the ceiling and retreat of the drip line has resulted in deposition of blocky roof fall (*éboulis*) visible in the excavation profile. Aghitu-3 (Upper Paleolithic), Armenia (Photo credit: Andrew W. Kandel). (**c**) A small secondary cavity shelter formed due to differential erosion at the contact between an ash-flow tuff and the underlying soil (*arrow*), possibly exacerbated by the abrasive activities of livestock (see Brochier et al., 1992). This shelter may be a type of pseudokarst. Aksaray Province, Turkey. (**d**) The shelter and related features in (**c**) have been recently utilized as a sheep stabling area. The *arrow* indicates the position of the shelter pictured in (**c**). Sheep dung accumulates as sediment and is concentrated here, as both the cliff face and the overhang at the tuff soil contact provide protection from wind and sun. Man-made cavities and shelters have been carved into a lower tuff – likely during Byzantine times – and today are incorporated into the stabling area. These areas contain thick deposits of partially degraded dung and other organic materials. Aksaray Province, Turkey.



Rockshelter Settings, Figure 2 Karstic shelters. (**a**) This limestone shelter formed as a result of collapse of a former karstic chamber. Speleothems (*SP*) formed within a large karstic system, remnants of which are still present, and today, these features are eroded and are visible along the shelter wall. The sediments infilling the shelter are also largely eroded; however, beachrock (*BR*) deposits (cemented littoral sands and cobbles) are locally preserved. Blocks of roof fall (*RF*) are visible in the foreground and are related to collapse of the former cave ceiling as a result of tectonic activity. Archaeological deposits overlying the beachrock are capped with cave wall speleothems and flowstones. This stratigraphic relationship indicates that the earliest Paleolithic occupation of the site postdated a drop in sea level and predated a major phase of cave collapse. Scale is 3 m. Üçağızlı Cave II (Middle Paleolithic), Hatay Province, Turkey. (**b**) The Hohlenstein Stadel complex contains phreatic tubes, as well as rockshelters formed in limestone. Lone Valley (Upper Paleolithic), Germany (Photo credit: Jennifer Ort).

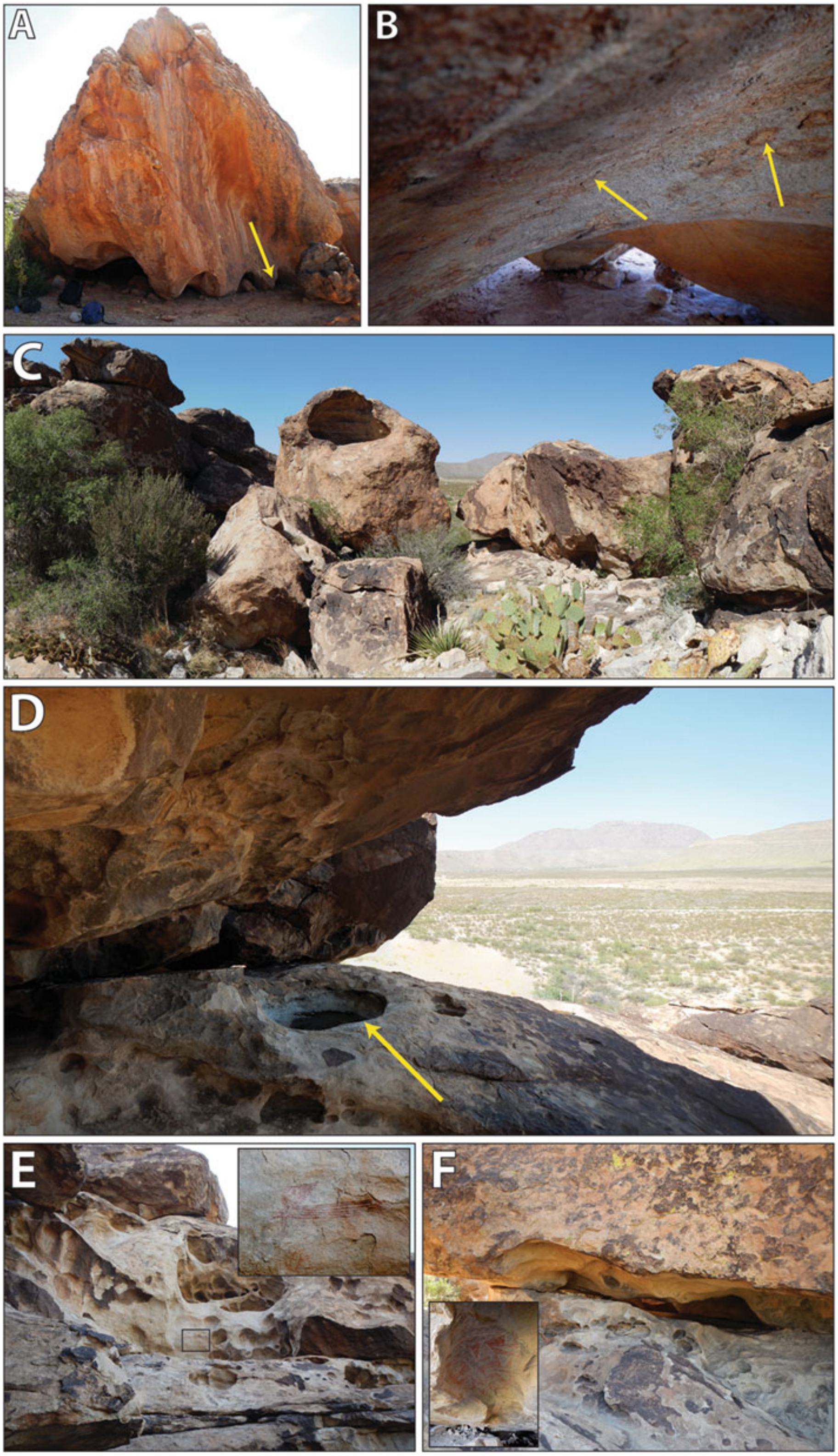
percolating solutions, or growth of ice causing individual particles to detach from the bedrock or boulder. These processes, along with thermal shock and insolation weathering, can also impact sand- and gravel-sized aggregates of material (see Figure 4b), the latter producing exfoliation when bedrock expands and contracts in response to heat. Tafoni and other spall features are common on vertical cliff faces and boulders. Of the many concave features, which include honeycombs, hollows, alveoli, lattices, alcoves, visors, and tortoiseshell rocks, only some are large enough to be exploited for human purposes, although smaller features such as basins and alcoves might be utilized as water sources and pictograph sites (see Figure 4c–f). Tafoni cavities can develop internal conditions that are cooler and moister than the surrounding environment, thus accelerating erosional and biological processes within the sheltered areas and contributing to their expansion (Cooke et al., 1993). Examples of archaeological localities located within tafoni are Hollow Rock, a Middle Stone Age shelter located in South Africa (see Figure 4a, b), and portions of the Hueco Tanks site in the USA (see Figure 4c–f). Salt weathering and cryoclastic processes can also operate at a variety of scales, producing other types of spall shelters in environments that are outside the typical range for tafoni. In the site of Sibudu, salt spalling and biological weathering have largely contributed to the present-day morphology of the site (see Figure 3b, also Goldberg et al., 2009). In high latitudes and elevations, freezing and thawing of water within bedrock cracks and joints can impact existing shelters and contribute to rockshelter sedimentary deposits (see below).

Abrasion shelters (Figure 5) form as a result of scouring and differential weathering by particles entrained in a fluid, such as air, water, or glacial ice. The location of an abrasion shelter within its host landform is determined by the position of the fluid source, as well as internal differences in bedrock type that influence their resistance to weathering. Abrasion shelters that form as a result of wind typically form by winnowing of individual mineral grains or clasts from soft bedrock by silt- and sand-sized particles entrained in the wind. Yardangs are elongate, wind-scoured features that can contain narrow concavities along their edges. Wind eddies along cliffs can also produce hollow cavities, usually with rounded morphologies. Abrasion of bedrock and boulders by sedimentary particles and ice carried by flowing water or waves can occur along rivers and streams, lake margins, and coastlines. The resulting features typically exhibit horizontal morphologies (see Figure 5a), although focusing of flow in waves and waterfalls and differential erosion can produce



Rockshelter Settings, Figure 3 Etchform shelters and cliff face and scarp-foot weathering processes. (**a**) Collapse of large blocks along the face of a kopje (*arrow*) – possibly aided by tectonic activity – has formed a shelter in sandstone. Diepkloof Rock Shelter (Middle and Later Stone Age), Western Cape Province, South Africa (see also Miller et al., 2013). (**b**) Salt spalling and biological activity have contributed to granular disintegration and cliff face retreat of sandstone along bedding planes (*arrow*), forming a large, amphitheater-like shelter. Fluvial activity also contributed to the formation of this site; however, the geogenic component of the sedimentary sequence is autochthonous fine material derived from weathering of the shelter walls and larger bedrock fragments. Sibudu Cave (Middle and Later Stone Age), Eastern Cape Province, South Africa (see also Goldberg et al., 2009). (**c**) A basal notch shelter along a limestone cliff contains archaeological materials of varied age. Basal notches form as a result of biological activity and increased moisture at the interface between soil and bedrock along a cliff. Subsequent erosion can expose these features for human exploitation. Sokobanja, Serbia.

cavities of varied shape. In water, abrasion weathering can be further compounded by biological activity, such as dissolution and boring by mollusks. In marine settings, biological activity can play a significant role in the formation of tidal notches and nips (Pirazzoli, 1986), which can reach depths of up to several meters. Humans may utilize active abrasion shelters as harbors for boats, while river channel migration and changes in base level, regional moisture, and lake and sea levels can expose inactive cavities for human habitation (e.g., Mehlman, 1979). Finally, glacial scouring can produce horizontal cavities along bedrock outcrops, and isolated erratics and boulders in till piles can provide local sources of shelter in high elevation or high-latitude settings. Abrasion shelters form in a variety of environmental settings, but they are most commonly created in easily eroded sedimentary bedrock types. Along coastlines, abrasion shelters can develop in uplifted coral reefs. Archaeological examples



Rockshelter Settings, Figure 4 (Continued) of abrasion shelters include Rodgers Shelter, USA, and the Middle and Upper Paleolithic sites of Abric Romaní and Abric Agut in Spain (Vallverdú-Poch et al., 2012).

Tectonic movements can result in the formation of cavities (Figure 6, also Figure 3a) and can contribute to the modification of shelters of all types. Faulting and folding of brittle rocks can produce fault breccias and loose clastic deposits that can erode once exposed to surficial weathering processes. For example, portions of the Zhoukoudian site complex formed as a result of erosion of fault breccias (Goldberg et al. 2001). Steeply angled fault scarps may also form small rockshelters. In addition, earthquake activity can contribute to the collapse of existing karstic caves (see Figure 2a) and etchplanation or cliff face features (see Figure 3a).

Pseudokarstic cavities (Figure 7) are highly transient types of shelters that form in surficial deposits, such as semi-consolidated sediment, tuff, tufa, marl, travertine, and easily eroded fine-grained intrusive dikes and sills. Archaeological sites located within collapsed pseudokarst may initially be classified as open-air settings. The Lower Paleolithic site of Dmanisi (Republic of Georgia) contains several collapsed pseudokarstic shelters that formed as a result of piping of volcanic ash. Man-made shelters, such as those carved into the soft ash-flow tuffs of Central Anatolia (see Figure 1d), are difficult to classify but can be considered as types of pseudo-cavities.

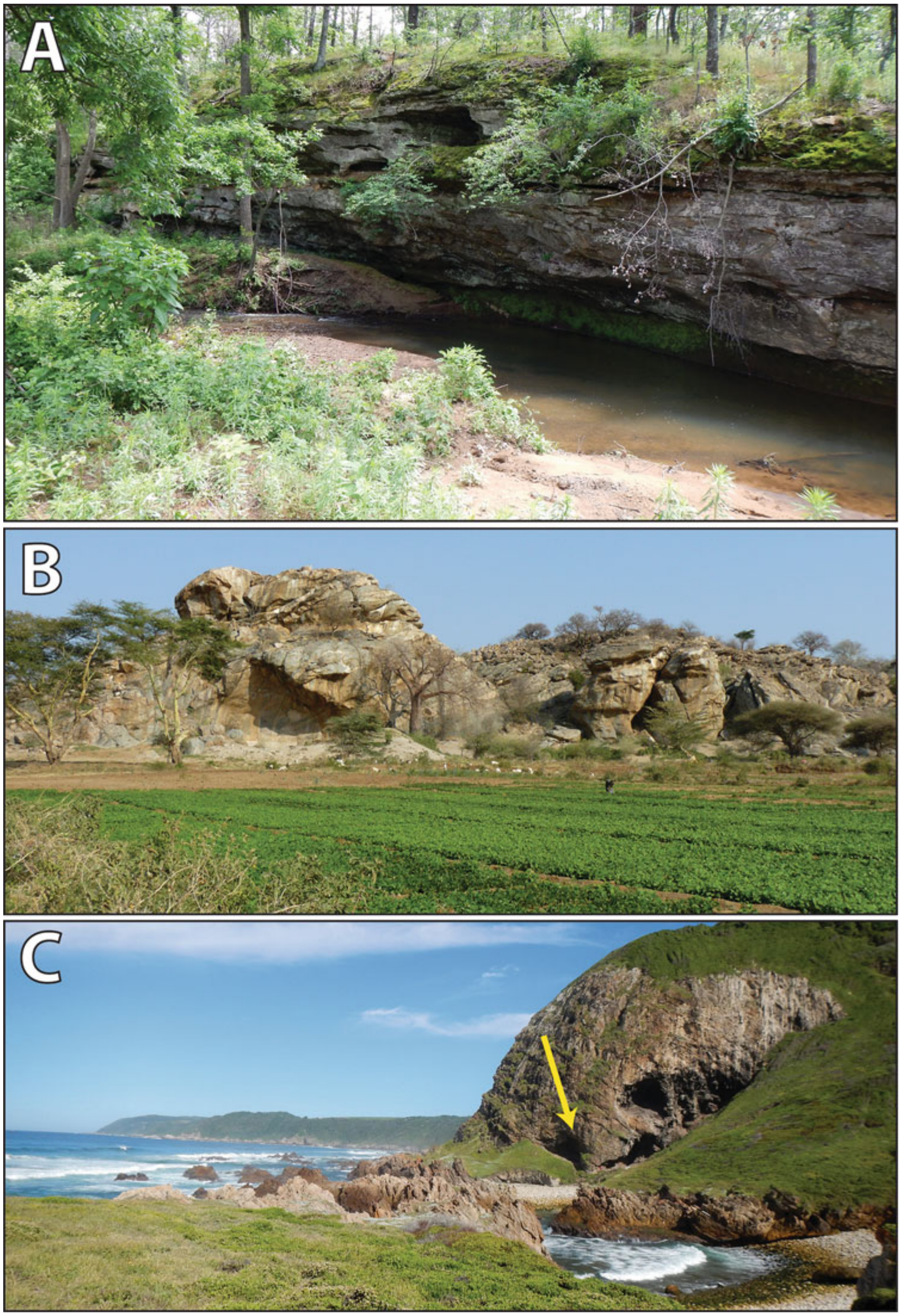
Sedimentation in rockshelters

According to Farrand (2001), sedimentation in rockshelters is idiosyncratic. The depositional and post-depositional processes are similar to those of cave entrances. In archaeological contexts, there are often a minimum of two sediment sources. First, roof blocks or bedrock fragments accumulate within most sites, and second, human beings function as depositional agents (Farrand, 2001). However, several types of formation processes described above are not conducive to the accumulation of sediment, although remnants of human activities may still be present. For example, in wind-scoured abrasion shelters, the same processes that contribute to the formation of the cavities are responsible for winnowing of fine materials from the shelter floors. In the Hueco Tanks tafoni shelters illustrated in Figure 4, erosional processes outpace accumulation, and sedimentary deposits are scarce. Nevertheless, petroglyphs (see Figure 4e, f), abrasive residues from clothing, and other modifications to the bedrock surfaces remain.

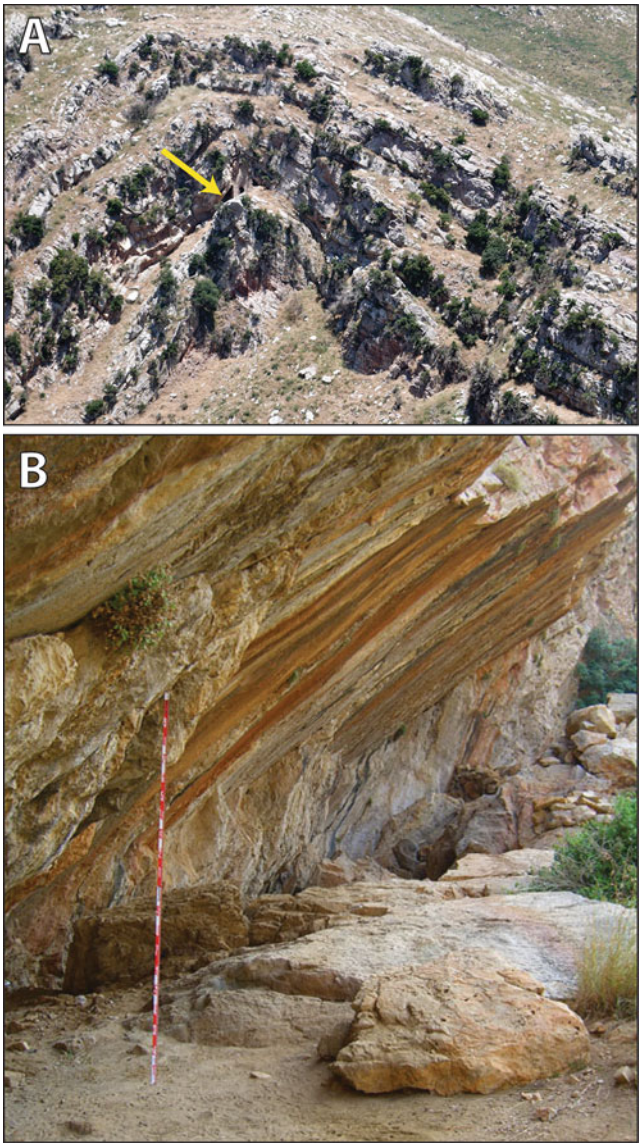
In other types of shelter, sedimentary deposits accumulate, and their sources are geogenic, biogenic, or anthropogenic. Furthermore, geogenic sources can be autochthonous (endogenous), related to both primary and secondary cavity formation processes, or allochthonous (exogenous). There are innumerable potential sources for sediment in rockshelter sites, including the bedrock, groundwater systems, rivers, lakes, oceans, slopes, wind, plants and animals, and humans. These sources and their depositional processes are described in more detail in Table 2. In addition, Figures 1b, 2, 3b, 4b, 5, and 6b include or illustrate settings in which different types of geogenic materials might accumulate, while selected biogenic and anthropogenic deposits are shown in Figures 8 and 9 (for herbivore dung, see Figure 1d).

Table 2 includes a number of sediment types that are not unique to rockshelter settings. Indeed, the extreme variety of rockshelter formation processes practically guarantees an almost limitless combination of ways to fill them. Although alluvial, fluvial, colluvial, and lacustrine sediments located in open-air and rockshelter settings share many features in common (e.g., presence of laminations, textural sorting, flow fabrics), a few depositional processes are unique in their expression within rockshelter sites. These processes include a specific type of eolian accumulation, "doming" (Davis, 1990, 337), wherein deposition is influenced by patterns of airflow and attenuation of currents at the entrance to the shelter. Doming causes the majority of windblown particles to accumulate in the center of the chamber. In addition, rockshelter morphologies – in particular the presence of a ceiling or overhang – can yield rockfall, spall, and attrition deposits with little to no lateral displacement from beneath their source. The drip line, or the line formed by dripping from the edge of the roof overhang (if present), can become a zone of accretion or erosion, depending on the environmental setting. In rainy settings, water falling over the brow of the cavity can contribute to erosion of sediment, in particular,

Rockshelter Settings, Figure 4 Tafoni shelters in sandstone and intrusive volcanic bedrock. (**a**) A tortoiseshell rock formed at the base of a sandstone boulder was exploited during the Middle Stone Age. *Arrow* shows the two low entrances pictured in (**b**). Hollow Rock, Western Cape Province, South Africa. (**b**) Shelter formation processes are ongoing, as evidenced by visible salt spalling, which has loosened cm-scale flakes of sandstone on the interior ceiling (*arrows*). The thin sedimentary deposits contain autochthonous geogenic materials derived from internal weathering; however, surface runoff contributes to erosion as well as allochthonous sedimentation as evidenced by rills that transverse the site. (**c**) Numerous types of tafoni shelters formed in syenite are visible here, including boulder shelters, alcoves, and tortoiseshell rocks. Hueco Tanks State Park, Texas, USA. (**d**) These shelters were exploited during the Holocene, from the Paleo-Indian period to the present, for protection from elements, as well as for surface water, which accumulates in circular pools and natural basins (*arrow*) – a *hueco* (Spanish for hollows). Here, erosional processes outpace sedimentation, and internal deposits are thin to nonexistent. (**e**) Tafoni features were also used as localities for Archaic and Formative Period rock art (pictograph visible in inset). (**f**) Erosion along a bedrock joint created a small shelter, the ceiling of which was utilized for artistic purposes (*inset*).



Rockshelter Settings, Figure 5 Abrasion rockshelters and entrainment shelters. (**a**) A horizontal shelter, approximately 3 m in height, carved by a stream flowing along sandstone. The sediments filling the shelter are fluvial in origin. Non-archaeological locality near Goodson Shelter, Oklahoma, USA. (**b**) A series of shelters was carved by wave abrasion of an inselberg formed in gneiss. Cavities are present at similar elevations, and portions of the sedimentary deposits are lacustrine in origin, both of which suggest that the formation and infilling of the sites are related to former high lake levels. Mumba Rockshelter (Middle and Later Stone Age), East African Rift, Tanzania (see also Mehlman, 1979) (Photo credit: Nicholas J. Conard). (**c**) A small shelter (*arrow*) formed, in part, by wave abrasion near a complex of sea caves in quartzite. Sedimentation in the site is complicated but includes eolian components related to coastal dunes and anthropogenic materials. Klasies River main site (1B; Middle Stone Age), Tsitsikamma Coast, Eastern Cape Province, South Africa (see also Butzer, 1978).



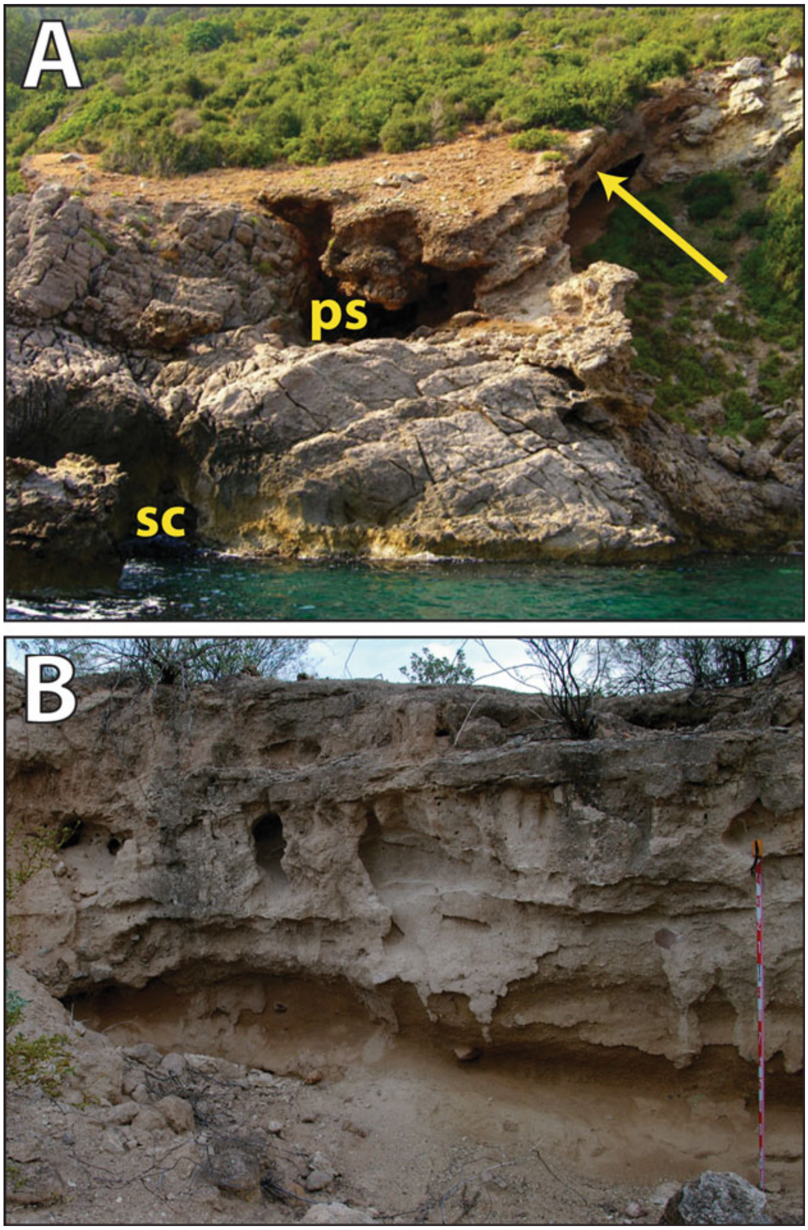
Rockshelter Settings, Figure 6 Tectonic shelters. (**a**) A shelter formed in the axis of an anticline fold in limestone (*arrow*) was used by Greek villagers in the nineteenth century as a refuge against Ottoman invasions. Mt. Lykaion, Peloponnesus, Greece (Photo credit: George H. Davis, Mt. Lykaion Excavation and Survey Project). (**b**) A small limestone shelter formed along joint planes related to a fault scarp. Scale is 2 m. Sedimentary deposits within this site are limited to autochthonous geogenic materials, primarily large slabs of roof fall. Non-archaeological locality near Üçağızlı Cave II, Hatay Province, Turkey.

washing of fine materials. The accumulation of large blocks of roof fall along the drip line also locally influences the direction of sediment movement, in some cases producing a characteristic downward slope of sediment into the shelter (e.g., Farrand, 1975). These depositional patterns can result in spatial variability in sediment accumulation rate and surface morphology. Furthermore, in contrast to open-air sites, depositional mechanisms and post-depositional processes can vary laterally within meters of space.

Post-depositional processes further contribute to the nature of the stratigraphic sequences observed by archaeologists working in rockshelter sites. Like primary depositional processes, post-depositional modifications can be generated by geological, biological, or human agents. Many of the geogenic depositional processes in Table 2 can contribute to post-depositional reworking of sediments within rockshelters. For example, waves can both deposit materials and move them laterally within sites, while wind can deposit fine-grained materials, or winnow, leaving lag deposits. Furthermore, post-depositional processes and their relative impacts can be influenced by environmental factors (e.g., cryoturbation), as well as the composition and structure of the over- and underlying primary deposits – e.g., chemical diagenesis (Karkanas, 2010), or effects of human foot traffic (Hughes and Lampert, 1977). Post-depositional geological processes that are unique to rockshelter and cave entrance settings include pooling, ponding, and washing by water flow focused at the drip line.

Soil-forming processes, although limited in some cave environments, can occur within rockshelters. For example, Angelucci (2003) describes weak soils and pedofeatures developed in sediments located in Abric Cantivera, Spain; similar processes impacted the deposits at Akrotiri, Cyprus. Other soil-forming processes that impact rockshelter sediments include decalcification, calcite recrystallization, precipitation of carbonates at depth, clay translocation, humification, and bioturbation by insects, rodents, and larger animals (Braillard et al., 2004). In other types of sites, such as dry shelters, soil-forming processes can be completely inactive, with very localized hyperaridity preventing humification and other biological activities and as a consequence preserving rich organic sequences (Davis, 1990).

Erosional processes – both related and unrelated to cavity-forming processes – can impact rockshelters in various ways. On a basic level, erosion can remove sediments of all types and produce depositional unconformities in the stratigraphic sequences. Erosional events can be localized, or like some sedimentation processes described above, can be proxies indicating regional climatic events. Humans can contribute to erosional processes within shelters by intentionally removing or modifying sediment in order to obtain resources such as guano or animal dung (Brochier et al., 1992) or to change the internal organization of space (Hughes and Lampert, 1977). Thus, evidence for erosion can have implications for human behavior. Erosion can also significantly complicate the interpretation of the archaeological record. For example, Mercader et al. (2003) state that in the Ituri rockshelters of the Congo, regional erosional processes have biased the history of human occupation toward the most recent 20,000 years. O'Connor et al. (1999) review similar



Rockshelter Settings, Figure 7 Pseudokarstic shelters. (**a**) A pseudokarstic shelter (*ps*) formed in calcite-cemented colluvium. The bedding layers within the colluvium are visible along an eroded face (*arrow*). Only the upper portion of the deposit is cemented by pedogenic carbonate, which acts as a caprock and contributes to differential erosion of the underlying loose sediment. An actively forming sea cave (*sc*) and marine notch in limestone are also visible in the foreground. These types of feature, when exposed due to uplift or lowered sea level, may be used as shelters. Non-archaeological locality near Üçağızlı Cave I, Hatay Province, Turkey. (**b**) Small cavities formed due to differential erosion of layers of palustrine and pedogenic carbonates. Non-archaeological locality near the El Fin del Mundo complex of sites (Paleo-Indian), Sonora, Mexico (Photo credit: Vance T. Holliday).

processes in Australian sites and note that (1) proper identification of erosion events (in some cases, evidenced by lag deposits) and hiatuses in deposition and (2) the distinction between these and hiatuses in occupation are essential for understanding regional responses of human populations to the effects of Pleistocene environmental change. O'Connor et al. conclude by proposing a number of analytical methods and strategies that might be employed in future studies to address this issue.

Sedimentological analyses in rockshelter sites

High variability in shelter formation processes, landscape and environmental settings, and human activities within

Rockshelter Settings, Table 2 Sediment types and potential sources in archaeological rockshelter sites

Sediment type	Depositional process	Main characteristics	References and/or archaeological example
Geogenic, autochthonous			
Mass wasting: rock fall	Many; tectonic activity, freeze-thaw, salt weathering	Coarse blocks and slabs of bedrock, degraded bedrock	Donahue and Adovasio (1990); see also Figures 1b and 2a; e.g., Akrotiri *Aetokremnos*
Insoluble residues, “cave earth”	Granular disintegration following chemical weathering, localized reworking by water	Fine materials that are present as inclusions within the bedrock	Woodward and Bailey (2000)
Mass wasting: attrition, spall	Granular disintegration due to salt weathering, hydration weathering, frost spalling	Texture, composition, and rounding of mineral grains are determined by the bedrock	Donahue and Adovasio (1990), see also Figures 3 and 4; e.g., Akrotiri *Aetokremnos*
Chemical: travertine, some tufa	Precipitation from alkaline springs in karstic settings can include biological activity	Typically calcareous with variable crystal size, fabric, and degree of cementation	Mallol et al. (2009), Vallverdú-Poch et al. (2012); see also Figure 8d
Geogenic, allochthonous			
Infiltration	Material from outside the bedrock system transported into the shelter through cracks and conduits	Composition is variable; texture determined by size of conduits and mode of transport	Woodward and Bailey (2000); e.g., Akrotiri *Aetokremnos*
Fluvial and alluvial	Deposition of clastic materials by flowing water or rivers	Variable composition, texture, and sorting; laminations	Farrand (1979), Woodward et al. (2001); see also Figure 5a; e.g., Rodgers Shelter
Lacustrine	Mechanical and chemical deposition within lakes	Variable composition, texture, and sorting	Mehlman (1979), Woodward and Goldberg (2001); see also Figure 5b
Marine/littoral	Deposition by water in near-shore environments, storm events	Variable composition, texture, and sorting	Woodward and Goldberg (2001); see also Figure 2
Colluvial	Mass wasting and movements of material down slopes	Poor textural sorting, flow fabrics	Mercader et al. (2003), Kourampas et al. (2009); e.g., Rodgers Shelter
Eolian	Deposition of material entrained in wind	High degree of sorting, typically fine sand- to silt-sized materials; volcanic ash	Byrne et al. (*1979*), Davis (1990); e.g., Akrotiri *Aetokremnos*
Biogenic			
Guano, coprolites, and non-anthropogenic herbivore dung	Digestive and urinary waste elimination by animals living within or utilizing the shelter	Typically high in phosphate content, can also contain abundant phytoliths, calcareous dung spherulites, gastroliths	Byrne et al. (*1979*), Davis (1990), Brochier et al. (1992), Braillard et al. (2004), see also Figure 8b
Middens, nests, and mounds	Accumulation and nesting activities of rodents, birds, and insects	Plant material, phytoliths, calcium oxalates, fecal pellets, urine-derived minerals,	Davis (1990), Wallis (2002), Scott et al. (2004), see also Figure 8a,b
Bone beds, owl pellets, shell accumulations	Residues of carnivory or death assemblages of animals living within the site	Bones and bone fragments; shell	Martin and Borrero (1997), Cremaschi and Negrino (*2005*)
Organic debris	Decay of plants growing inside or near the shelter, eolian biogenic materials (e.g., pollen)	Plant material in various states of humification, phytoliths, calcium oxalate crystals	Byrne et al. (*1979*)
Stromatolites, some tufa	Biogenic precipitation of calcium carbonate	Porous micrite with biological fabrics	Mallol et al. (2009); see also Figure 8d
Diatomite, diatomaceous earth	Algal bodies in standing and flowing water	Siliceous shells	
Anthropogenic			
Combustion features	Burning of wood and other fuels; sweeping or dumping of burned materials	Ashes, charcoal, burned substrates	Mentzer (2012), Miller et al. (2013); see also Figure 9a

Rockshelter Settings, Table 2 (Continued)

Sediment type	Depositional process	Main characteristics	References and/or archaeological example
Middens and refuse	Discard of food processing debris and other forms of trash	Variable	Hughes and Lampert (1977), Galanidou (2000); see also Figure 9b
Prepared surfaces, floors, bedding	Intentional modification of geogenic sediment within the shelter or transport of sediment and other materials for the purposes of constructing a floor or other forms of prepared surface	Beaten earth; mud, lime, dung, and gypsum plaster; organic material and phytoliths; mudbrick; stones	Galanidou (2000), Goldberg et al. (2009), see also Figure 9c
Stabling materials, livestock dung, *fumier*	Use of a shelter for the stabling of animals, commonly herbivores, bedding of birthing areas; periodic burning of dung	Typically high in phosphate content, often containing abundant phytoliths and calcareous dung spherulites; humified and/or burned organic material; rare inclusions of diatoms	Brochier et al. (1992), Angelucci et al. (2009), see also Figure 1d
Latrines	Human digestive and urinary wastes; caches of feces	Typically high in phosphate content, contain diagnostic coprostanols	

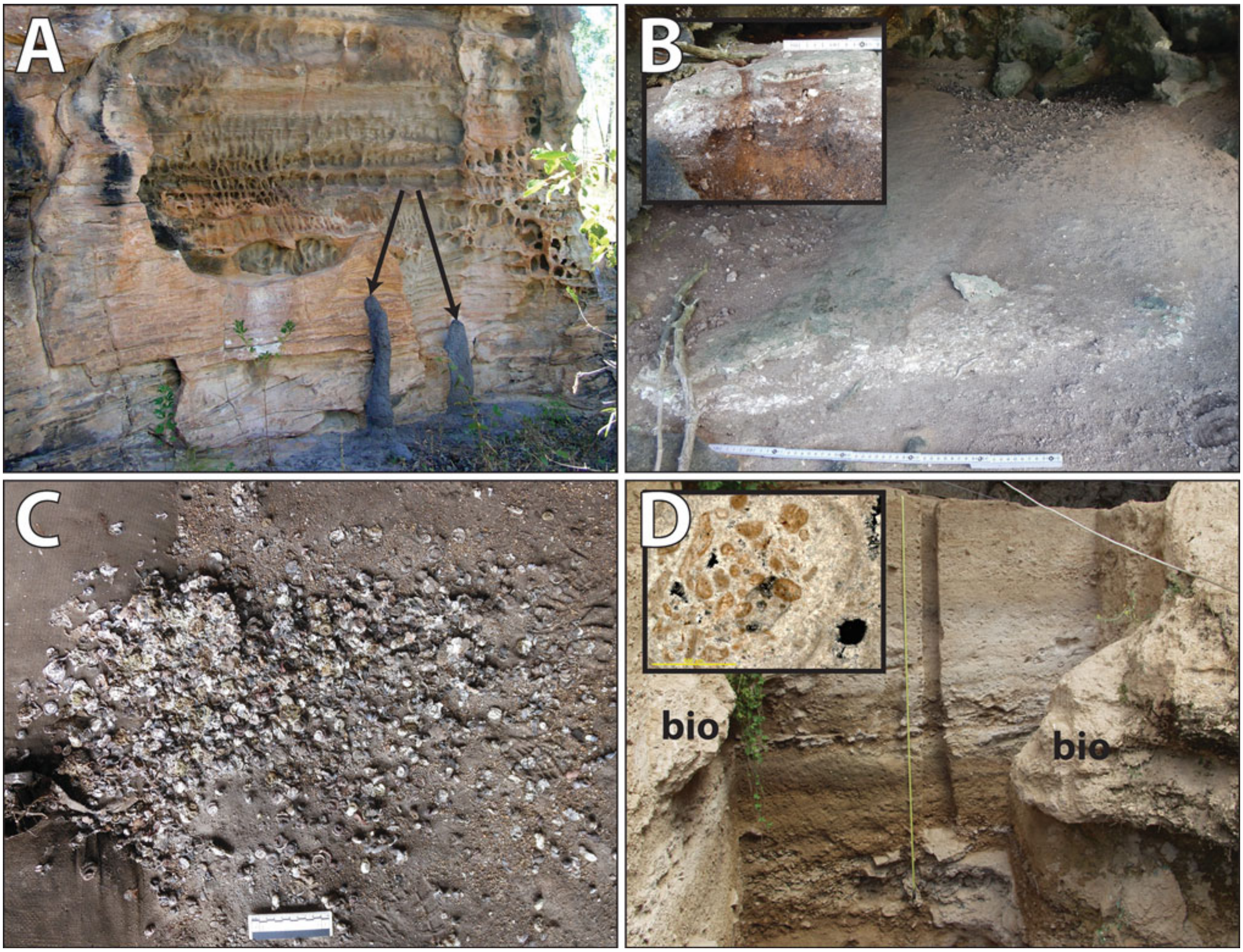
the sites yield a wide range of sedimentary sequences, such that there are no "rules" to follow when developing analytical strategies. As advocated by O'Connor et al. (1999), successful geoarchaeological analyses of rockshelter sequences aimed at understanding sedimentation history typically employ a mixture of approaches conducted at a variety of scales and target both "bulk" samples and in situ materials. These analyses include granulometry (grain size analysis), mineralogy and lithology (see also Woodward and Bailey, 2000), soil micromorphology and sedimentary petrography, magnetic susceptibility measurements, and chemical and elemental analyses. Of these, micromorphology is considered by some to be the most holistic approach, especially when analysts aim to understand anthropogenic sedimentation (Goldberg and Sherwood, 2006; Mentzer, 2012). Additional analyses may be employed in order to reconstruct paleoenvironmental conditions. For example, rockshelters may function as traps for pollen (Davis, 1990; Woodward and Bailey, 2000; Woodward and Goldberg, 2001). Furthermore, certain types of rockshelter deposits (e.g., chemical precipitates, organic materials, eolian silts) can be directly dated using radiometric techniques (U-series dating, radiocarbon dating, OSL, etc.) to reconstruct the timing of formation or deposition.

The choice of analytical methods can be constrained by the types of deposits that are present and the specific research questions related to paleoenvironmental reconstruction and human behaviors, including the desired resolution of the observations. Because rockshelter sequences are both unpredictable and influenced by a variety of conditions, a process-oriented approach to site formation is advocated (e.g., Ward and Larcombe, 2003). Testable models may be developed for specific types of rockshelters in similar landscape settings and environments (e.g., Donahue and Adovasio, 1990). Analytical priorities might be framed in terms of proximal and distal sources and processes (Woodward and Bailey, 2000).

Rockshelter life histories

As noted above, rockshelters are transient geomorphic features related to bedrock weathering processes and surface sediments. Rockshelter morphologies therefore change over time, including throughout the duration of their utilization by humans. Changes in rockshelter morphology have a number of possible consequences for their use as occupation areas and thus the potential for containing anthropogenic sediments, as well as for the overall preservation of archaeological deposits.

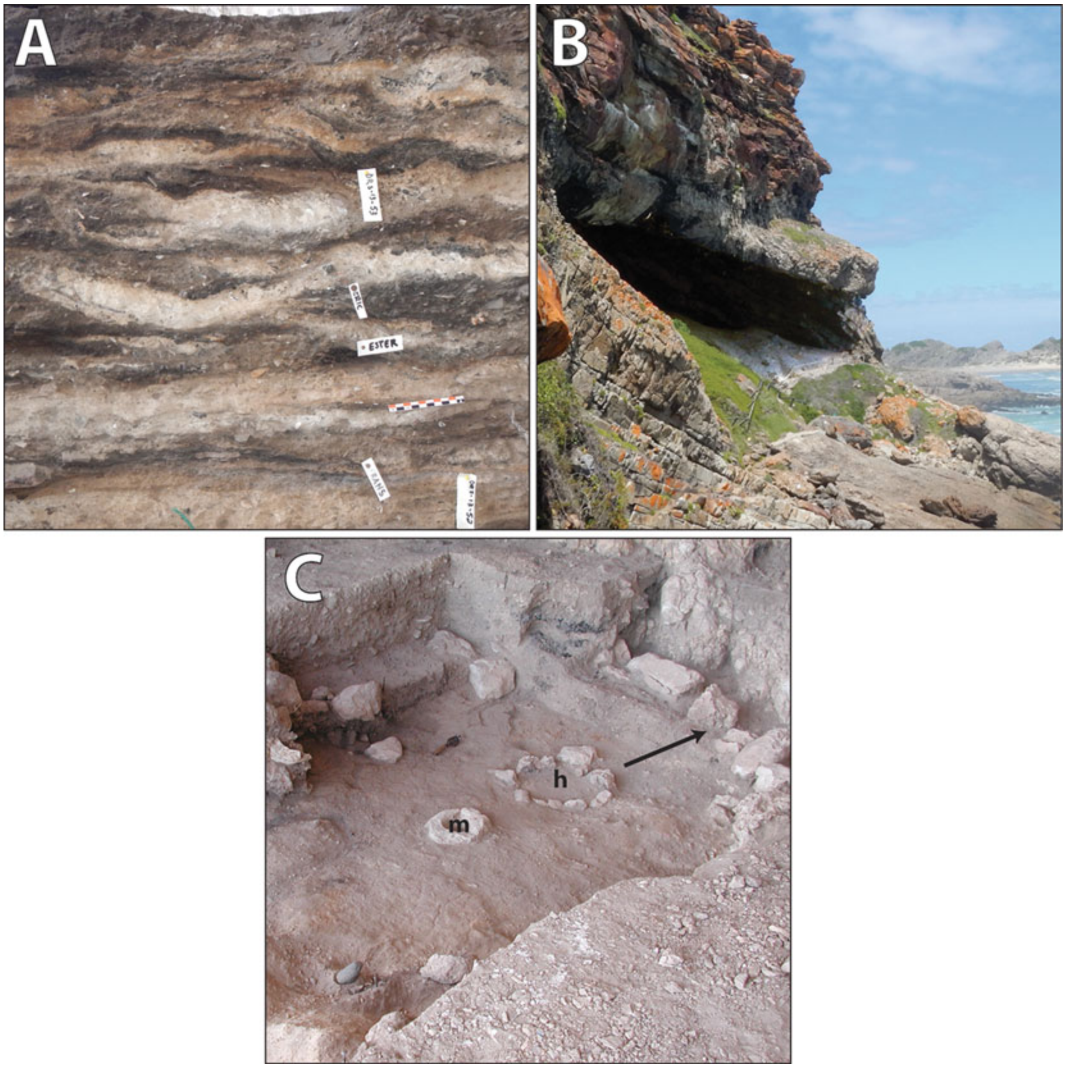
Shelters can become larger over time due to a combination of ongoing primary and secondary formation processes. Enlargement of shelters or migration of the position of walls and overhangs can produce complicated site stratigraphies. For example, in the well-studied sedimentary sequences at the Abri Pataud and Combe Grenal (France), both the bedrock morphology and the imbrications and positioning of roof block layers indicate gradual retreat of the bounding cliff faces during the occupation history of the sites (Bordes, 1972; Farrand, 1975; 2001). In the Abri Pataud, younger strata were positioned to the east with respect to older strata, and due to this progressive lateral shift in sedimentation, the entire sequence cannot be displayed in any single area of the site. When multiple layers are present, some of the younger layers are colluvial in origin or exhibit a marked slope compared



Rockshelter Settings, Figure 8 Different types of biogenic sedimentary deposits in rockshelters. (**a**) Termite mounds (*arrows*) within a sandstone tafoni shelter. Termites and other insects such as ants introduce material into shelters from outside, sort sediment by texture, modify or obliterate primary sedimentary fabrics, and consume and rework organic refuse. Tafoni features, including honeycomb rocks, are visible on the shelter wall above the mounds. Non-archaeological locality near Gledswood Shelter, Queensland, Australia (Photo credit: Kelsey Lowe). (**b**) A biogenic midden containing coprolites interbedded with plant-derived nesting material and partially cemented by urine. The inset shows the internal stratigraphy, which includes subsurface formations of nodular secondary minerals. This feature, which fills a small abrasion shelter, was accumulated by rock hyrax (dassies; *Procavia capensis*), although similar features can accumulate in North America through the actions of pack rats (*Neotoma* sp.). These types of deposit can contain rich paleoenvironmental records, e.g., pollen and insect carapaces (Davis, 1990; Scott et al., 2004), and they can also ignite and burn due to non-anthropogenic processes (e.g., forest fires and lightning strikes). Non-archaeological coastal locality in sandstone/quartzite near Blombos Cave, Western Cape Province, South Africa. (**c**) Bird guano and swallow nests (not pictured) accumulate in Diepkloof Rock Shelter, South Africa (see also Figure 3a), introducing organic material and allochthonous clay- and silt-sized sediment to the deposits. (**d**) Tufaceous materials can include biological components. Here, large, cemented bioconstructions (bio) and softer biogenic calcite layers are formed within a karstic limestone shelter. The inset is a photomicrograph of a sample of tufa under cross-polarized light illustrating a biological fabric. Obi-Rakhmat Grotto (Middle Paleolithic), Uzbekistan (see also Mallol et al., 2009) (Photo credit: Patrick J. Wrinn).

to the older layers. In many cases, enlargement has finite limits. According to Farrand (2001), enlargement of rockshelters can yield more usable space for periods of time, but this process ultimately makes the shelter more susceptible to collapse.

Collapse of portions or the entirety of a rockshelter overhang can contribute significantly to sedimentation at the site. This phenomenon is evidenced in stratigraphic sequences as layers of roof fall (see Table 2). For this reason, rockshelter sequences are particularly poor



Rockshelter Settings, Figure 9 Anthropogenic deposits in archaeological rockshelters. (**a**) Thick deposits of ashes and charcoal are sourced from Middle and Later Stone Age burning activities at the site of Diepkloof Rock Shelter (see Miller et al., 2013; also Figure 3a here). In some rockshelters, burned materials can comprise the majority of sediments infilling the cavities. (**b**) A large Khoisan (4000–3000 BP) shell midden fills Hoffman's/Robberg Cave on the Robberg Peninsula, Western Cape Province, South Africa (see also Kyriacou and Sealy, 2009). (**c**) The upper surface of a *red-colored*, constructed earthen floor with an embedded mortar (*m*) and rock-lined hearth (*h*). The rock wall (*arrow*) marks the edge of the structure that was built within the limestone shelter and is associated with the floor. Humans may contribute to sedimentation in a rockshelter by utilizing local materials for construction purposes or by intentionally transporting material into the site. Baaz Rockshelter (Natufian), Syria (see also Conard, 2002) (Photo credit: Andrew W. Kandel).

candidates for calculation or interpretation of sedimentation rate (O'Connor et al., 1999). Continued weathering and collapse can also lead to complete destruction of the shelter, limiting or preventing the recovery of archaeological materials. An example of this phenomenon is the complete erosion of all but two Pleistocene rockshelter sites in the Ma'aloula and Jaba'deen localities of Syria (Conard, 2002).

In this light, the role of a geoarchaeologist working on excavations within rockshelters is not only to consider the combined impacts of infilling, erosion, and morphological change on the preservation of archaeological deposits but also to address and interpret within this framework the variations in human activities that occurred over time. For example, infilling of a small space could reduce available headroom, which in turn could cause a number of changes in human behavior, including abandonment of the site, shifting from regular to occasional habitation, or intentional modification of the substrate. Collapse of portions of a shelter can likewise impact human utilization, change local erosional regimes thereby causing removal of archaeological deposits, or seal and protect the underlying archaeological sediments from further erosion and weathering (an example would be Akrotiri *Aetokremnos*). These interrelated aspects of rockshelter life histories can make archaeological sequences within them particularly challenging to reconstruct.

Summary and conclusions

The preceding sections have provided a comprehensive overview of (1) rockshelter formation, including archaeological examples and expected distributions grouped according to a classification system organized by the primary processes of cavity development, (2) a catalogue of sediment sources and types of deposits, (3) analytical techniques employed in the study of rockshelter sediments, and (4) approaches to the reconstruction of rockshelter life histories. The goal of geoarchaeology in reconstructing rockshelter life histories is not only to understand the formation processes of the sites but to aid in the interpretation of the archaeological record. By the definitions outlined above, rockshelters must afford their occupants some relief from the elements, including extreme heat or cold, direct light, wind, and precipitation. For this reason, in combination with their relatively high visibility on the landscape, intact rockshelters can be targets of archaeological survey. The likelihood of their exploitation in the past is intuitive; however, rockshelter deposits can be highly variable and are often difficult to categorize owing to, in some cases, complicated combinations of allochthonous and autochthonous geogenic processes, as well as contributions from biological and human activity.

Acknowledgment

William R. Farrand (1931–2011) laid the foundation to a comprehensive framework for the study of rockshelter sequences and, in doing so, influenced and motivated a generation of geoarchaeologists, including the author, whose work here depends greatly on his research.

Bibliography

Angelucci, D. E., 2003. Geoarchaeology and micromorphology of Abric de la Cativera (Catalonia, Spain). *Catena*, **54**(3), 573–601.

Angelucci, D. E., Boschian, G., Fontanals, M., Pedrotti, A., & Vergès, J. M. (2009). Shepherds and karst: the use of caves and rock-shelters in the Mediterranean region during the Neolithic. *World Archaeology*, **41**(2), 191–214.

Barton, C. M., and Clark, G. A., 1993. Cultural and natural formation processes in late Quaternary cave and rockshelter sites of western Europe and the Near East. In Goldberg, P., Nash, D. T., and Petraglia, M. D. (eds.), *Formation Processes in Archaeological Context*. Madison: Prehistory Press, pp. 33–52.

Binford, L. R., 1996. Hearth and home: the spatial analysis of ethnographically documented rock shelter occupations as a template for distinguishing between human and hominid use of sheltered space. In Conard, N. J., and Wendorf, F. (eds.), *Middle Palaeolithic and Middle Stone Age Settlement Systems: Actes du XIII congrès de préhistoire et de sciences protohistoriques, volume 6, tome 1, Forli, Italie, 8–14 septembre 1996*. Tübingen: Kerns, pp. 229–239.

Byrne, R., Busby, C., & Heizer, R. F. (1979). The Altithermal revisited: pollen evidence from the Leonard Rockshelter. *Journal of California and Great Basin Anthropology*, 280–294.

Bordes, F., 1972. *A Tale of Two Caves*. New York: Harper and Row.

Braillard, L., Guélat, M., and Rentzel, P., 2004. Effects of bears on rockshelter sediments at Tanay Sur-les-Creux, southwestern Switzerland. *Geoarchaeology*, **19**(4), 343–367.

Brochier, J. E., Villa, P., Giacomarra, M., and Tagliacozzo, A., 1992. Shepherds and sediments: geo-ethnoarchaeology of pastoral sites. *Journal of Anthropological Archaeology*, **11**(1), 47–102.

Butzer, K. W., 1971. *Environment and Archaeology: An Ecological Approach to Prehistory*. Chicago: Aldine.

Butzer, K. W., 1978. Sediment stratigraphy of the Middle Stone Age sequence at Klasies River Mouth, Tsitsikama coast, South Africa. *The South African Archaeological Bulletin*, **33**(128), 141–151.

Butzer, K. W., 1981. Cave sediments, upper pleistocene stratigraphy and mousterian facies in Cantabrian Spain. *Journal of Archaeological Science*, **8**(2), 133–183.

Collcutt, S. N., 1979. Analysis of quaternary cave sediments. *World Archaeology*, **10**(3), 290–301.

Conard, N. J., 2002. An overview of the recent excavations at Baaz Rockshelter, Damascus Province, Syria. In Aslan, R., Blum, S., Kastl, G., Schweizer, F., and Thumm, D. (eds.), *Mauer Schau: Festschrift für Manfred Korfmann*. Remshalden: Verlag Berhard Albert Greiner, Vol. 2, pp. 623–640.

Cooke, R. U., Warren, A., and Goudie, A., 1993. *Desert Geomorphology*. London: UCL Press.

Cremaschi, M., & Negrino, F. (2005). Evidence for an abrupt climatic change at 8700 14C yr BP in rockshelters and caves of Gebel Qara (Dhofar-Oman): Palaeoenvironmental implications. *Geoarchaeology*, **20**(6), 559–579.

Davis, O. K., 1990. Caves as sources of biotic remains in arid western North America. *Palaeogeography Palaeoclimatology Palaeoecology*, **76**(3–4), 331–348.

Donahue, J., and Adovasio, J. M., 1990. Evolution of sandstone rockshelters in eastern North America: a geoarchaeological perspective. In Lasca, N. P., and Donahue, J. (eds.), *Archaeological Geology of North America*. Boulder: Geological Society of America. Centennial Special, Vol. 4, pp. 231–251.

Farrand, W. R., 1975. Sediment analysis of a prehistoric rockshelter: the Abri Pataud. *Quaternary Research*, **5**(1), 1–26.

Farrand, W. R., 1985. Rockshelter and cave sediments. In Stein, J. K., and Farrand, W. R. (eds.), *Archaeological Sediments in Context*. Orono: Center for the Study of Early Man, pp. 21–39.

Farrand, W. R. (1979). Chronology and palaeoenvironment of Levantine prehistoric sites as seen from sediment studies. *Journal of Archaeological Science*, **6**(4), 369–392.

Farrand, W. R., 2001. Sediments and stratigraphy in rockshelters and caves: a personal perspective on principles and pragmatics. *Geoarchaeology*, **16**(5), 537–557.
Ford, D., and Williams, P. W., 2007. *Karst Hydrogeology and Geomorphology*. Chichester: Wiley.
Funk, R. E., 1989. Some contributions of archaeology to the study of cave and rockshelter sediments: examples from eastern New York. *Man in the Northeast*, **37**, 35–112.
Galanidou, N., 2000. Patterns in caves: foragers, horticulturists, and the use of space. *Journal of Anthropological Archaeology*, **19**(3), 243–275.
Goldberg, P., Weiner, S., Bar-Yosef, O., Xu, Q., & Liu, J. (2001). Site formation processes at Zhoukoudian, China. *Journal of Human Evolution*, **41**(5), 483–530.
Goldberg, P., and Sherwood, S. C., 2006. Deciphering human prehistory through the geoarcheological study of cave sediments. *Evolutionary Anthropology: Issues, News, and Reviews*, **15**(1), 20–36.
Goldberg, P., Miller, C. E., Schiegl, S., Ligouis, B., Berna, F., Conard, N. J., and Wadley, L., 2009. Bedding, hearths, and site maintenance in the Middle Stone Age of Sibudu Cave, KwaZulu-Natal, South Africa. *Archaeological and Anthropological Sciences*, **1**(2), 95–122.
Heydari, S., 2007. The impact of geology and geomorphology on cave and rockshelter archaeological site formation, preservation, and distribution in the Zagros Mountains of Iran. *Geoarchaeology*, **22**(6), 653–669.
Hughes, P. J., and Lampert, R. J., 1977. Occupational disturbance and types of archaeological deposit. *Journal of Archaeological Science*, **4**(2), 135–140.
Karkanas, P., 2010. Preservation of anthropogenic materials under different geochemical processes: a mineralogical approach. *Quaternary International*, **214**(1–2), 63–69.
Kourampas, N., Simpson, I. A., Perera, N., Deraniyagala, S. U., and Wijeyapala, W. H., 2009. Rockshelter sedimentation in a dynamic tropical landscape: late Pleistocene-early Holocene archaeological deposits in Kitulgala Beli-lena, Southwestern Sri Lanka. *Geoarchaeology*, **24**(6), 677–714.
Kyriacou, K., and Sealy, J., 2009. *The Archaeological Assemblage from the 1958 Excavation of Hoffman's/Robberg Cave and a Comparison with Nelson Bay Cave*. Bloemfontein: Nasionale Museum. Navorsinge van die Nasionale Museum, **25**(2).
Mallol, C., Mentzer, S. M., and Wrinn, P. J., 2009. A micromorphological and mineralogical study of site formation processes at the late Pleistocene site of Obi-Rakhmat, Uzbekistan. *Geoarchaeology*, **24**(5), 548–575.
Martin, F. M., & Borrero, L. A. (1997). A puma lair in Southern Patagonia: implications for the archaeological record. *Current anthropology*, **38**(3), 453–461.
McDonald, R. C., and Twidale, C. R., 2011. On the origin and significance of basal notches or footcaves in karst terrains. *Physical Geography*, **32**(3), 195–216.
Mehlman, M. J., 1979. Mumba-Hohle revisited: the relevance of a forgotten excavation to some current issues in East African prehistory. *World Archaeology*, **11**(1), 80–94.
Mentzer, S. M., 2012. Microarchaeological approaches to the identification and interpretation of combustion features in prehistoric archaeological sites. *Journal of Archaeological Method and Theory*, **21**(3), 616–668.
Mercader, J., Martí, R., González, I. J., Sánchez, A., and García, P., 2003. Archaeological site formation in rain forests: insights from the Ituri Rock Shelters, Congo. *Journal of Archaeological Science*, **30**(1), 45–65.
Miller, C. E., Goldberg, P., and Berna, F., 2013. Geoarchaeological investigations at Diepkloof Rock Shelter, Western Cape, South Africa. *Journal of Archaeological Science*, **40**(9), 3432–3452.
O'Connor, S., Veth, P., and Barham, A., 1999. Cultural versus natural explanations for lacunae in Aboriginal occupation deposits in northern Australia. *Quaternary International*, **59**(1), 61–70.
Pirazzoli, P. A., 1986. Marine notches. In van de Plassche, O. (ed.), *Sea-Level Research: A Manual for the Collection and Evaluation of Data*. Norwich: Geo Books, pp. 361–400.
Scott, L., Marais, E., and Brook, G. A., 2004. Fossil hyrax dung and evidence of Late Pleistocene and Holocene vegetation types in the Namib Desert. *Journal of Quaternary Science*, **19**(8), 829–832.
Straus, L. G., 1990. Underground archaeology: perspectives on caves and rockshelters. *Journal of Archaeological Method and Theory*, **2**, 255–304.
Sweeting, M. M., 1973. *Karst Landforms*. New York: Columbia University Press.
Twidale, C. R., and Vidal Romani, J. R., 2005. *Landforms and Geology of Granite Terrains*. Leiden: A.A. Balkema Publishers.
Vallverdú-Poch, J., Gómez de Soler, B., Vaquero, M., and Bischoff, J. L., 2012. The Abric Romaní site and the Capellades region. In Carbonell i Roura, E. (ed.), *High Resolution Archaeology and Neanderthal Behavior: Time and Space in Level J of Abric Romaní (Capellades, Spain)*. Dordrecht: Springer, pp. 19–46.
Ward, I., and Larcombe, P., 2003. A process-orientated approach to archaeological site formation: application to semi-arid northern Australia. *Journal of Archaeological Science*, **30**(10), 1223–1236.
Wallis, Lynley A. AMS Dates and Phytolith Data from Mud Wasp and Bird Nests at Carpenter's Gap1, Northern Australia. Australian Archaeology, No. 55, Dec 2002: 35–39.
Ward, I. A. K., Fullagar, R. L. K., Boer-Mah, T., Head, L. M., Taçon, P. S. C., and Mulvaney, K., 2006. Comparison of sedimentation and occupation histories inside and outside rock shelters, Keep-River region, northwestern Australia. *Geoarchaeology*, **21**(1), 1–27.
Woodward, J. C., and Bailey, G. N., 2000. Sediment sources and terminal pleistocene geomorphological processes recorded in rockshelter sequences in northwest Greece. In Foster, I. (ed.), *Tracers in Geomorphology*. London: Wiley, pp. 521–551.
Woodward, J. C., Hamlin, R. H. B., Macklin, M. G., Karkanas, P., & Kotjabopoulou, E. (2001). Quantitative sourcing of slackwater deposits at Boila rockshelter: a record of lateglacial flooding and Paleolithic settlement in the Pindus Mountains, Northwest Greece. *Geoarchaeology*, **16**(5), 501–536.
Woodward, J. C., and Goldberg, P., 2001. The sedimentary records in Mediterranean rockshelters and caves: archives of environmental change. *Geoarchaeology*, **16**(4), 327–354.

Cross-references

Akrotiri Aetokremnos, Cyprus
Alluvial Settings
Analysis of Carbon, Nitrogen, pH, Phosphorus, and Carbonates as Tools in Geoarchaeological Research
Cave Settings
Coastal Settings
Dmanisi
Dumps and Landfill
Eolian Settings: Loess
Fourier Transform Infrared Spectroscopy (FTIR)

Grain Size Analysis
Hearths and Combustion Features
Living Surfaces
Optically Stimulated Luminescence (OSL) Dating
Organic Residues
Paleoenvironmental Reconstruction
Paleoshores (Lakes and Sea)
Pastoral Sites
Pre-Clovis Geoarchaeology
Privies and Latrines
Radiocarbon Dating
Shell Middens
Site Formation Processes
Soil Micromorphology
Spring Settings
Susceptibility
Trampling
U-series Dating
Volcanoes and People
X-ray Diffraction (XRD)
Zhoukoudian

S

SANTORINI

Floyd W. McCoy
Department of Natural Sciences, University of Hawaii – Windward, Kane'ohe, HI, USA

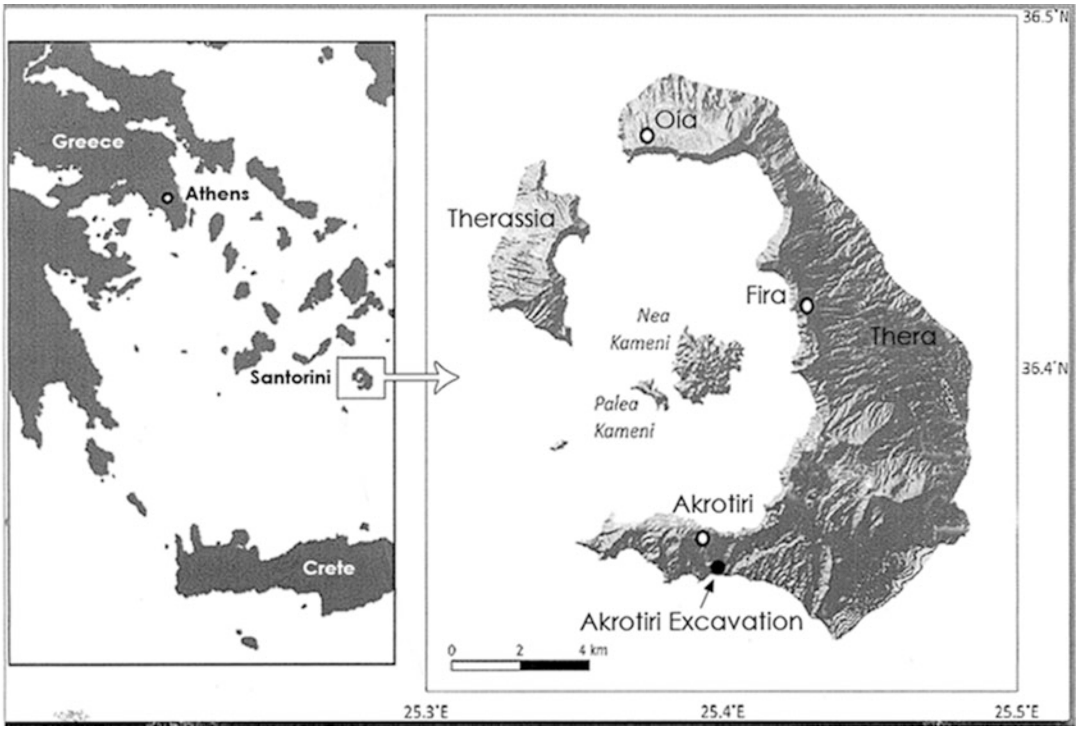
Santorini is the modern name for a collection of small islands in the southern Aegean Sea, the southernmost group in the Cyclades Islands. The ancient name is Thera, which is also the geographic name for the largest of the five islands in this archipelago (the other four are Therasia, Aspronisi, Nea Kameni, and Palaeo Kameni) (Figure 1). Theras, from Sparta, established a colony here in the fifth century BCE. Another ancient name is Kalliste, mentioned by Apollonius in the myth of Jason and the Argonauts in apparent reference to a spectacular geographic setting created by a ring of islands surrounding a water-filled depression within which were additional islets that today have either subsided below sea level or been merged into Nea Kameni island. "Santorini" refers to the entire island cluster, and this name was applied during Venetian occupation of the islands from the early thirteenth century AD in reference to Santa Irini, the patron saint of sailors (who is reputedly buried on Therasia). The official government designation for the archipelago is "Thera" or "Thira," depending upon the transliteration of the Greek "θηρα."

Santorini is best known for an enormous explosive eruption that occurred approximately 3600 years ago. The eruption of Thera is considered the largest volcanic event in the past 10,000 years and one of the largest in human antiquity (McCoy and Dunn, 2002; Druitt, 2014; Johnston et al., 2014; and references therein); it devastated local and regional cultures, and it fueled later legends. The eruption occurred in the Late Bronze Age (LBA) of the archaeological ceramic chronology developed for the Aegean. In the geologic chronology, the eruption was simply the latest explosive affair in a long sequence of such events, some of which may have been more than twice the size of the LBA event (Keller et al., 2014) (Figure 2).

The consequence of this last eruption is the current Santorini archipelago, which forms one of the grandest landscapes on earth, a stunning geomorphological feature created by spectacular episodes of volcanism (Figure 3). The islands are the summit of a largely underwater volcanic feature, and the surface expression is more appropriately referred to as a volcanic field rather than a "volcano." An assortment of eruptive vents and their products (tephra and lava flows) are exposed here and represent repeated episodes of volcanic activity over the past 645,000 years. The result is a dramatic and astounding scenic feature defined by a central water-filled caldera encompassing two small central islands where current volcanic activity is concentrated. This caldera has emerged from repeated, highly explosive, Plinian-type eruptions, each having excavated portions of this depression to form the modern feature. Repeat times for major explosive eruptions are on the order of about 20,000 years, although this has been hugely variable.

Effusive volcanism during the intervals between Plinian eruptions has been less explosive (see Figure 2), characterized by Strombolian-Pelean-type activity with minor accumulations of tephra but extensive outpourings of thick (a'a and block) lava flows and extrusion of domes. Some of these eruptions constructed large shield-shaped structures, relics of two being the Skaros area on Thera and the modern island of Therassia. Volcanism as it exists today on the Kameni islands represents the volcano in a rebuilding stage. Interestingly, this rebuilding has apparently never constructed a high and lofty cone-shaped feature such as characterizes volcanoes such as Fujiyama or

A.S. Gilbert (ed.), *Encyclopedia of Geoarchaeology*, DOI 10.1007/978-1-4020-4409-0,

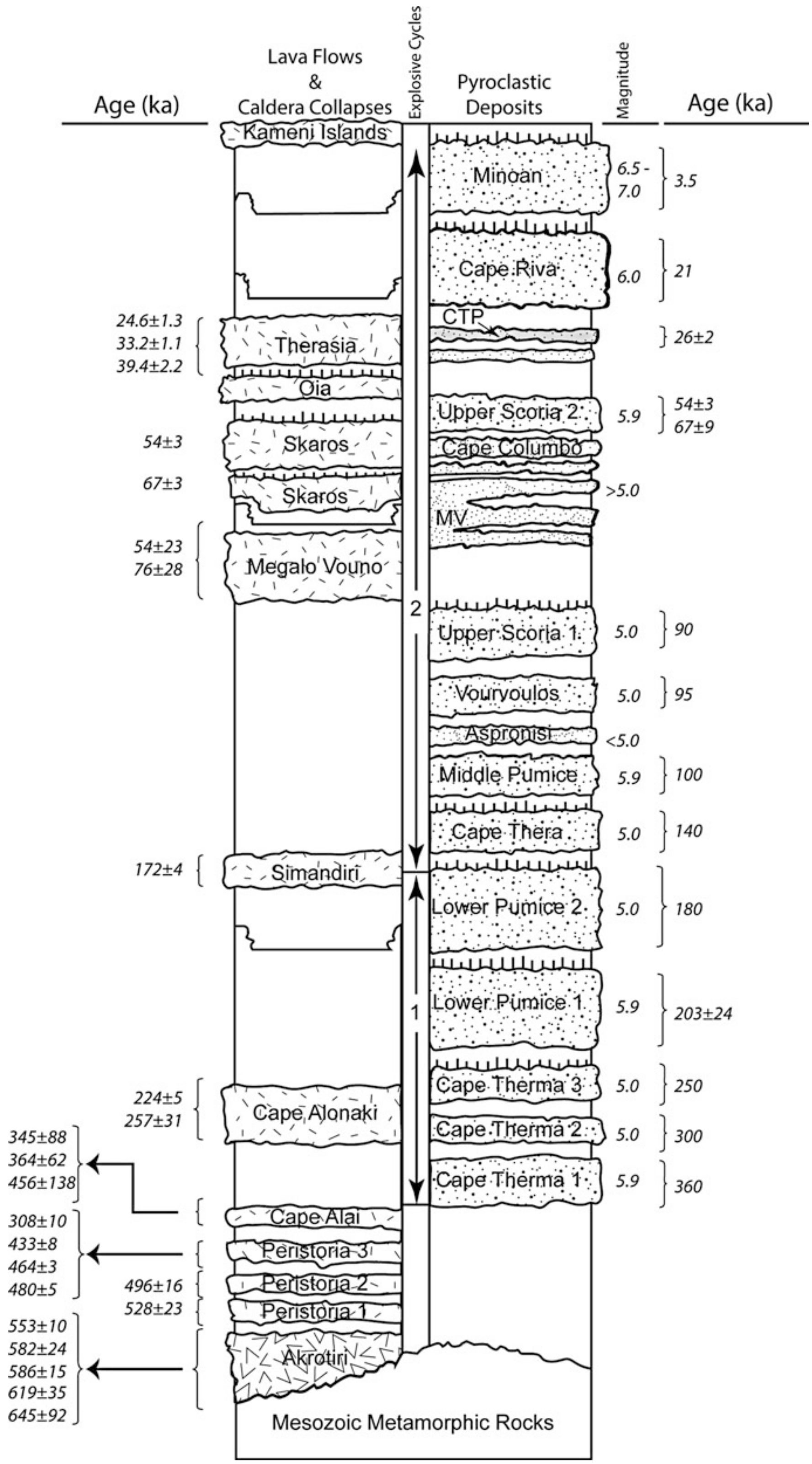


Santorini, Figure 1 The modern geography of Santorini, an archipelago of five islands surrounding a water-filled volcanic caldera. Current volcanism is focused on the island of Nea Kameni. Archaeological excavations have been conducted within the ancient city at Akrotiri, which was buried during the catastrophic eruption in the Late Bronze Age.

Mt. Aetna; a variable-sized caldera seems to have usually been a major physiographic feature of the Theran volcanic landscape. Prior reconstructions of the volcanic edifice before the LBA eruption imagined such a cone shape by extrapolation of outer topographic slopes in the modern geomorphology upward to form a peak centered over the modern caldera. Geologic evidence has shown this to be incorrect.

The last huge eruption – which was a 2–4 day event – occurred while the island was occupied by a flourishing Cycladic culture in the LBA. This eruption was far larger than the 1980 eruption of Mt. St. Helens and greater than that of Krakatau in 1883 and the 1815 Tambora eruption (Figure 4). It must have been an enormous shock to the inhabitants of Thera, who may have had no knowledge that they lived on a dangerous volcano, if they even understood volcanism, though they certainly enjoyed its benefits in the form of hot springs, fumeroles, mineral deposits, easily quarried and shaped stones, productive soils, and more. Their landscape, like today, was also a - water-filled caldera but with a large central island (Figure 5). Interestingly, a rendering of the pre-eruption LBA landscape seems to be portrayed in a portion of the Marine Fresco from the West House in the Akrotiri archaeological excavation, the only depiction left to us by an ancient artist (Doumas, 1992) (Figure 6).

The consequences of the LBA eruption to the Cycladians on Santorini and nearby Aegean islands, especially Crete, were catastrophic. An island central to trade by the Cycladians with surrounding Aegean cultures such as the Minoans on Crete was gone, now an altered inhospitable landscape of hot steaming ash and pumice. In the Aegean and eastern Mediterranean region, tephra fall, earthquakes, pumice rafts, tsunamis, violent thunderstorms, climate change, health hazards, and more contributed to crippling these ancient societies (for a summary of the geologic consequences, see McCoy and Heiken, 2000; for societal consequences, see Driessen and MacDonald, 1997). Tephra clouds reached as far north as the Black Sea and perhaps as far southeast as the Nile Delta. Tsunamis radiated out from Santorini north into the Aegean, south to Crete, then eastward to the shores of the Levant and the Nile Delta, as well as westward into the Ionian Sea, assuredly with significant damage to ancient ports. It must be emphasized that numerous tsunami wave sets were generated by numerous tsunamigenic mechanisms during the eruption. Within the Aegean Sea, with its relatively shallow water depths and scattered islands, tsunami



Santorini, Figure 2 (Continued)

wave interactions through wave reflections, wave refractions, and harmonic trapping of wave energy likely established complex wave patterns (seiches) that would have kept that sea in turmoil not only during the eruption but for some days afterward, with consequent erratic and repeated inundations along its coastlines. Whether there was significant climate change due to the eruption is yet to be established, as are human health effects such as from ash inhalation. Still to be determined is potential damage to surrounding islands by hot, low-density portions of pyroclastic flows that might have traversed the sea surface, a phenomenon documented in ancient and historic eruptions, and perhaps fatal to escaping Cycladians on boats at sea.

While the Minoan culture persisted for another few generations, it is clear that this cataclysm significantly contributed to their demise. Certainly the eruption terminated the Cycladian culture. An eruption of similar magnitude today would have a huge impact on the region, but for a culture 3600 years ago, it was a stunning disaster.

Yet the eruption preserved, virtually intact, a LBA city on the southern slopes of Thera at Akrotiri. Here, a city lies buried under volcanic ash, containing buildings, paintings and frescos, housewares, furniture, jewelry, and more. Limited damage to the town came during the latter phases of the LBA eruption when pyroclastic flows and lahars/debris flows eroded into already deposited tephra to damage structures (Figure 7). Much like Pompeii in AD 79, the Akrotiri site is a small city but almost twice as old; it is a spectacular archaeological site providing a window into a sophisticated culture of about 3600 years ago, certainly the "Pompeii of the Aegean" (Doumas, 1983).

A chronometric (absolute) date for the LBA eruption remains controversial. The relative dating scheme of the Aegean ceramic chronology indicates a date at, or very near, the final Late Minoan (LM) IA or perhaps into the following period LM IB. Carbon 14 dates on archaeological materials from stratigraphic horizons considered equivalent to the Aegean LM IA period found in excavations in the Aegean and the surrounding eastern Mediterranean region suggest a date of about 1500–1515 BCE, and this is termed the "low chronology" (Warren and Hankey, 1989; Wiener, 2007, and references therein). Additional criteria used to support this chronology come from analyses of records preserving accounts of ancient historical events and listings of ruler successions, the latter focused on Egyptian king/pharaoh lists. ^{14}C dates derived from trees buried within the tephra deposit on Santorini and presumably killed by the eruption, however, suggest a date of about 1600–1620 BCE, and this is referred to as the "high chronology." Additional criteria in support of this date come from ^{14}C dates of (1) materials found within LM IA contexts in the Aegean and surrounding regions; (2) acid-ice layers in Greenland ice cores; (3) deep-sea, marsh, and lake sediments encompassing tephra; (4) fossils incorporated within the tephra on Santorini; and (5) dendrochronological studies in Anatolia, Ireland, China, and California (Friedrich et al., 2006; Manning, et al. 2006; Warburton, 2009, and references therein). Historic records of severe climatological changes in China may also support this chronology. The discrepancy between the two chronological ranges is about 100 years or less. This is the consequence of, first, an inability to apply the current ^{14}C calibration curve for resolving the discrepancy (at exactly this time period, the curve is nonlinear and contains minor oscillations that make it difficult to assign a date with precision) and, second, an inadequate understanding of aspects in the carbon geochemical system. Clearly, another radiometric dating technique is called for to resolve the matter.

The LBA eruption probably occurred during the late spring–early summer. This information comes from using the regional distribution of ash found on land as a proxy for the atmospheric movement of the ash plume, then applying contemporary weather systems best suitable for tropospheric and stratospheric winds to cause this movement (assuming modern weather circulation patterns are similar to those during the LBA) (Sewell, 2001; McCoy, 2009; Johnston et al., 2012). Archaeological criteria provide additional support for this suggestion (Marinatos, 1939; Doumas and Papazoglou, 1980; Panagiotakopulu et al., 2013).

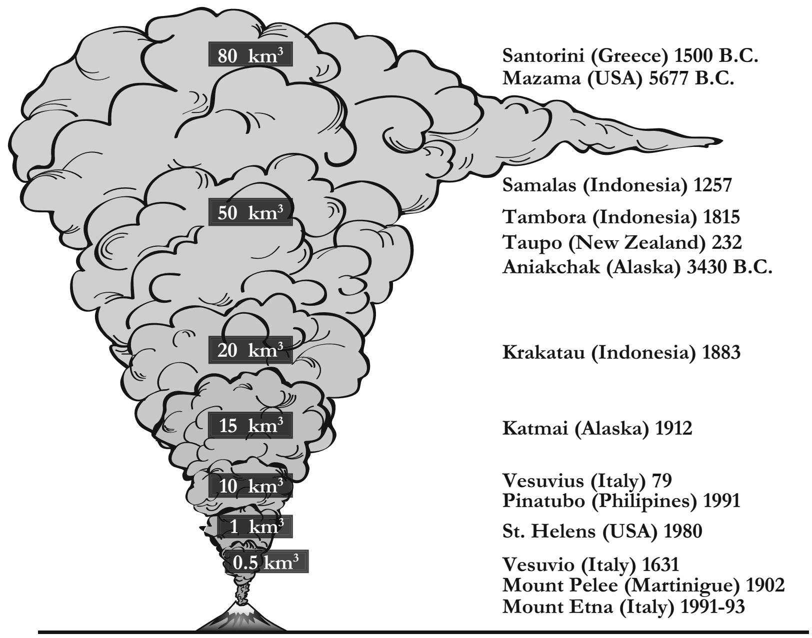
Volcanicity on Santorini speaks to two outstanding questions in volcanological research, both critical to understanding hazards and mitigation for contemporary cultures in similar settings. First, why was the LBA event so explosive, when other eruptions here in the past had not been as violent? Second, what are the repeat times for explosive eruptions, and can they be predicted? Certainly volcanoes typically producing quieter types of eruptions can be monitored and their activity somewhat predicted, such as in Hawaii, where much of this research has been done. Yet predicting how explosive an eruption might be

Santorini, Figure 2 Stratigraphic column exposed at Santorini depicting the eruption sequence over the last 645,000 years. Pyroclastic eruptions are depicted on the right and indicated by layers filled with a stippled pattern. The Thera Pyroclastic Series incorporates two major explosive cycles as indicated by numbers and arrows in the narrow central column (*MV* Megalo Vouno tephra). Eruption magnitudes noted follow the Volcanic Explositivity Scale, or VEI, of Newhall and Self (1982). Depicted on the *left* are eruptions that produced subaerial lava flows (fill consisting of randomly oriented dashes) and submarine flows (randomly oriented "v" pattern at the very bottom of the column: Akrotiri volcanics), in addition to major episodes of caldera collapse (*solid line* with *dropped middle portion*). Growth of paleosols is indicated by short *vertical lines* on *top* of various pyroclastic units and lava flows. Eruption ages in ka (1000 years before present) are given (Data are summarized from Druitt et al. (1999) and Friedrich (2000)).

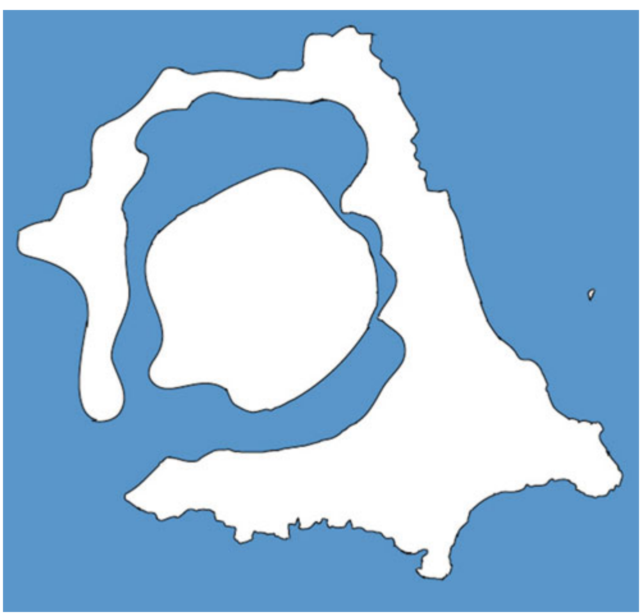
Santorini, Figure 3 Photograph looking west across the northern part of the water-filled caldera at Santorini. Surrounding the caldera are the islands of Thera (in the foreground and *right side* with a limited glimpse of the city of Fira on the *lower right* and the town of Oia in the distance appearing as a *white line* at the *top* of the caldera cliffs), Therassia (*far background*), and Nea Kameni (*left*) where current volcanic activity occurs in the form of steam vents, sulfur deposits, hot water springs, seismicity, and inflation/deflation events. The last eruption, a minor one, was here in 1950, and unrest in 2011–2012 signaled an intrusion of magma at depth that did not result in an eruption. The floor of the caldera lies more than 400 m below sea level, and the cliffs plunge straight down to those depths. Layers exposed in the caldera cliffs provide a dramatic record of volcanism over the past 700,000 years, as well as a geologic history from the Pliocene Epoch. The present caldera is the consequence of several highly explosive eruptions, the last occurring about 21,000 years ago (the Cape Riva eruption), and its configuration has persisted as a relatively stable geomorphological feature throughout much of the history of Santorini. In the Late Bronze Age, a flourishing Cycladic culture occupied a similar landscape of caldera cliffs with a much larger central island, but much was vaporized by the enormous eruption of 3600 years ago (Photograph courtesy of Walter L. Friedrich).

remains elusive outside of assuming somewhat equivalent timing based upon prior activity, which for Santorini seems about every 10,000–30,000 years (Druitt et al., 1999). Such repeat times are an order of magnitude more frequent than approximate repeat times for global eruptions of similar magnitude during the entire Quaternary (Brown et al., 2014). Current research focusing on magmatic plumbing systems and their interaction through injections of fresh magma, in addition to ascent times of magma to the surface, promise significant insights into understanding and perhaps predicting large eruptions (Cottrell et al., 1999; Jellinek and DePaolo, 2003; Parks et al., 2012; Druitt, 2014). Precursory activity to modern eruptions is well documented, and we can apply such activity to what the Cycladians on Santorini might have experienced prior to the explosion (likely no more than months in advance); it is assumed that some signals must have alerted the LBA inhabitants to leave since no fatalities related to eruption consequences have been found on Santorini, and archaeological evidence from the Akrotiri excavation suggests an abrupt and rapid evacuation of the island immediately prior to the disaster.

Why is a volcano sited here? Santorini is one of a dozen volcanic centers that formed behind, and in connection with, the southern Aegean island arc (Nomikou et al., 2013, and references therein). Here, tectonic closure (rates on the order of 5–6 cm/year) of the African continent against the European continent has created the Aegean Sea by the subduction of ancient seafloor attached to the African continent beneath the Aegean



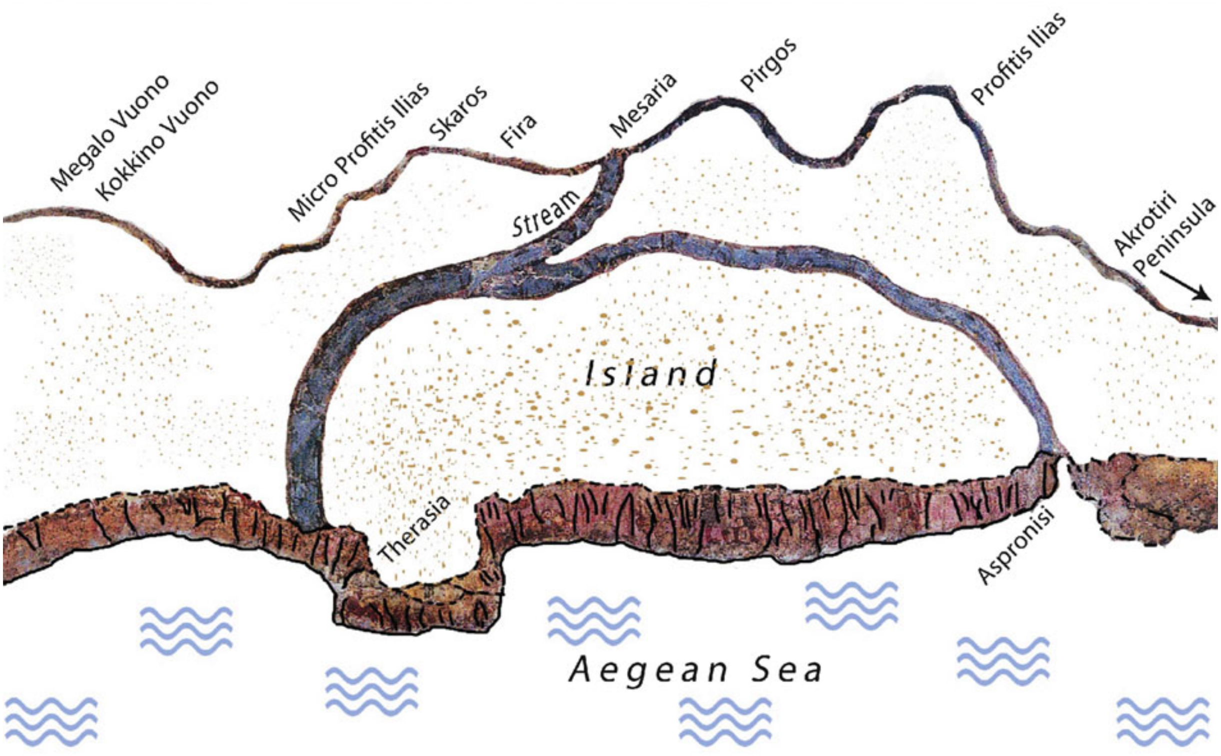
Santorini, Figure 4 Graphic representation of the relative explosiveness of the major eruptions during the past 3 millennia, as estimated by the volume of pyroclastic ejecta from that eruption (Data are from Druitt (2014), Johnston et al. (2014), and the Global Volcanism Program, Smithsonian Institution).



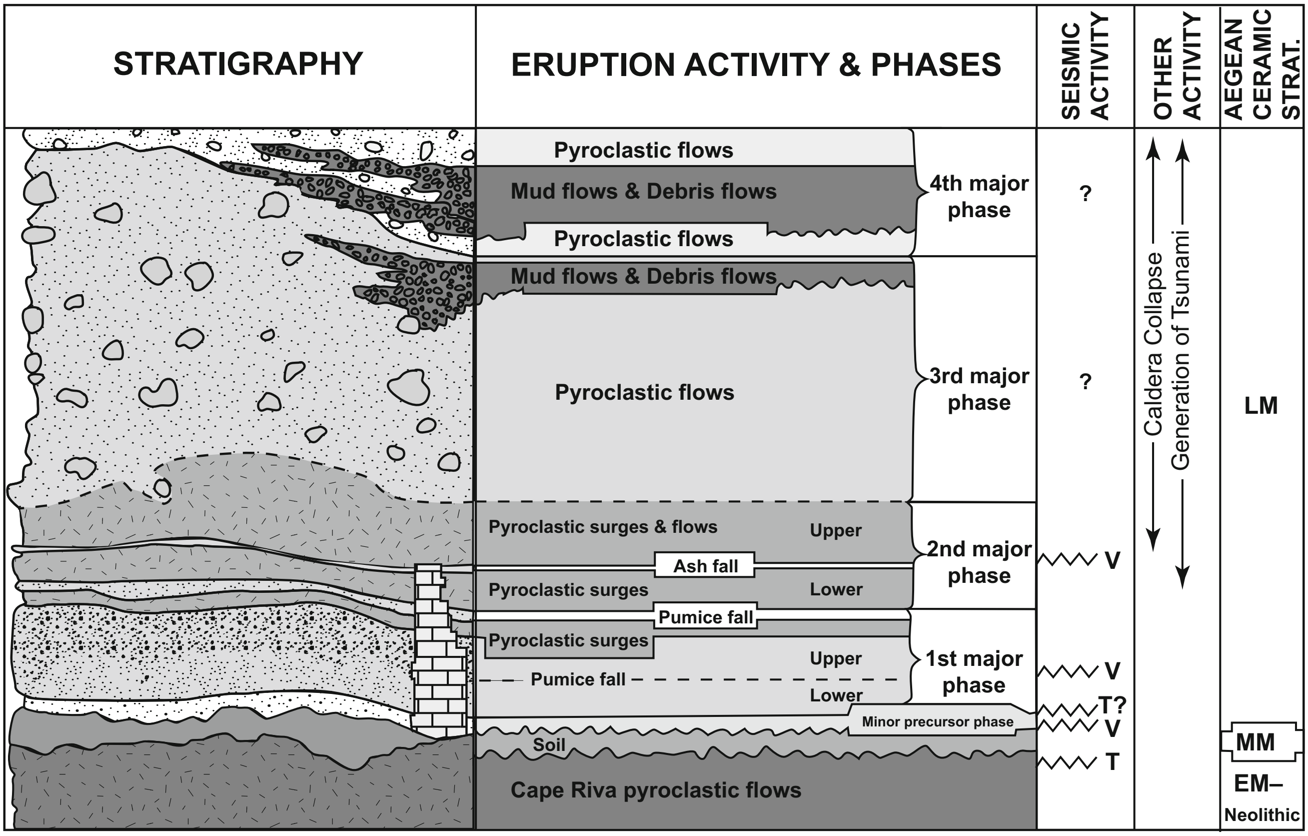
Santorini, Figure 5 Reconstruction of the ancient landscape of Thera prior to the massive LBA eruption. Then, as now, the geography generally described a central, water-filled caldera with a central island. As the figure shows, previous volcanism over 20,000 years or so had constructed a larger island prior to the LBA eruption than is seen today. The current configuration is the result of only 3600 years of volcanic activity to rebuild the two Kameni islands within the caldera. This depiction builds upon those proposed by Eriksen et al. (1990), Druitt and Francaviglia (1990, 1992), Druitt et al. (1999), Friedrich (2000), McCoy and Heiken (2000), Pfeiffer (2001), McCoy (2009), Druitt (2014), and others.

(Faccenna et al., 2014, and references therein). It is estimated that up to 850 km of lithosphere have disappeared beneath the Aegean seafloor over the past 38 Ma, dragged down into the deep hot mantle (Royden and Papanikolaou, 2011, and references therein). At depth, melting of the subducted seafloor occurs, producing magma that episodically rises to form these volcanic centers. Closure between Africa and the Aegean is enhanced by a complicated plate-tectonic pattern in the eastern Mediterranean region that results in a southern push of the Aegean against Africa, which is moving north. In short, the modern Mediterranean is being destroyed; it is, in essence, a modern remnant of far wider sea that existed during the Mesozoic era. In response to this tectonism, the Aegean crust is highly fractured and faulted. The Santorini volcanic field appears sited at an offset along one of these fractures, where a regional fault approximately orthogonal to the arcuate trend of the Aegean island chain intersects other fractures (Druitt et al., 1999) (Figure 8). Santorini represents only one of six major volcanic centers along this tectonic arc, all with geologic histories of eruptions, many violent; of them all, however, Santorini is certainly the most famous in mythology, history, science, and scenery. The consequence is a dynamic and dangerous setting.

Given this dramatic history and the geologic uncertainties accompanying this setting, it is interesting to find the reaction and concern of people living on Santorini today to volcanic hazards. In short, it is dismissed (Dominey-Howes and Minos-Minopoulos, 2004). As on other volcanoes, the hazards of living there are largely ignored, often not understood or not considered seriously.



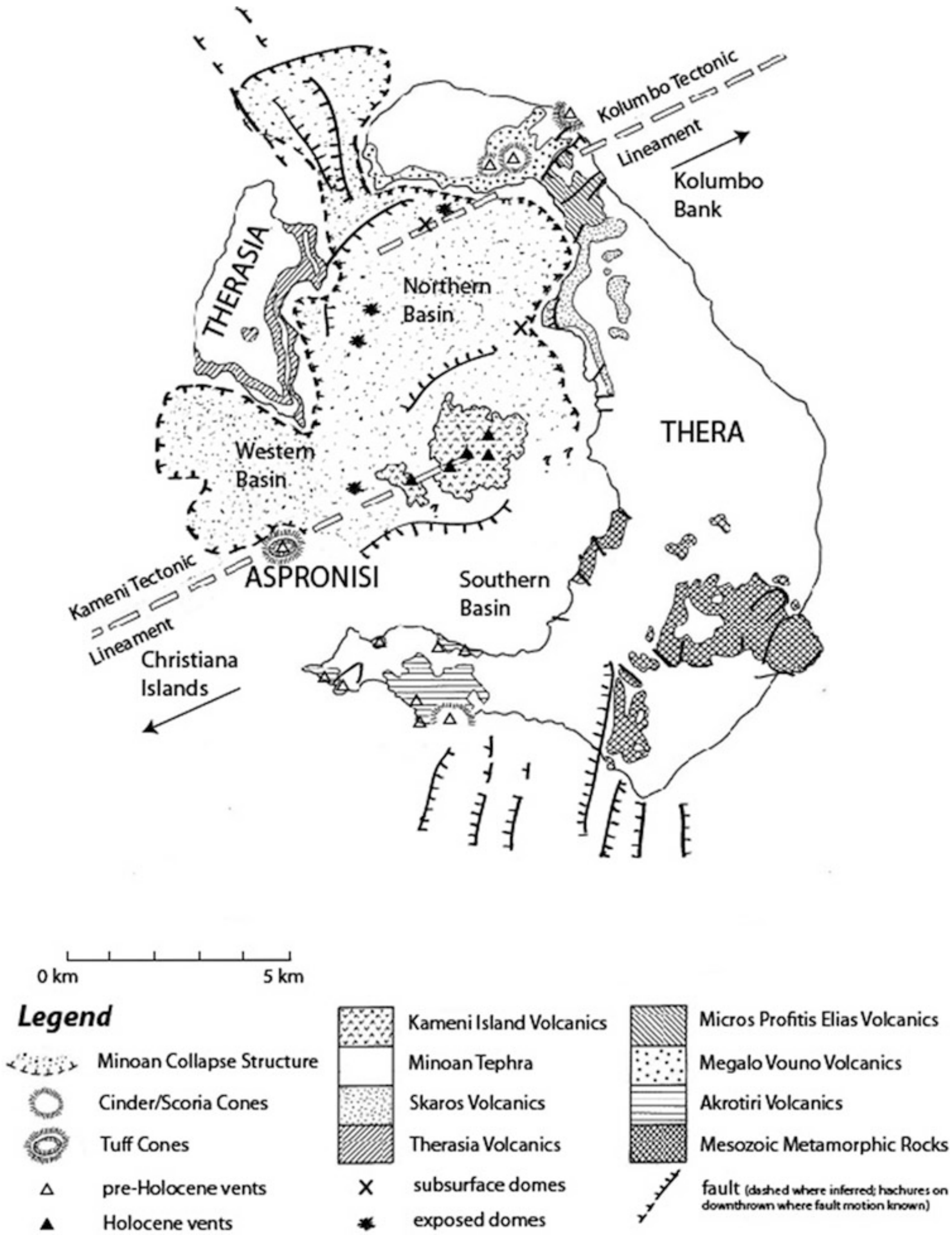
Santorini, Figure 6 (*Upper Panel*) A portion of the Marine Fresco as reconstructed from fragments found on the *upper* floor of the West House at the Akrotiri excavation (Doumas, 1992). It is argued that this scene represents the pre-eruption landscape by a Cycladic painter from a boat off the west coast of the island, looking toward the east, and depicting the physiography and skyline of the LBA landscape. (*Lower Panel*) Outline of the physiographic elements depicted in the Marine Fresco, with modern geographic names identifying prominent peaks that were not buried in tephra by the LBA eruption but remain today forming the modern skyline. This interpretation corroborates the reconstruction presented in Figure 5. Given the perspective in the LBA depiction, the western portion of the circular waterway surrounding the central island would not appear in the painting as it would have been hidden by the LBA Therassia-Aspronisi peninsula (see Figure 5). Note that a large city may occupy either the central island or the Therassia-Aspronisi peninsula and was subsequently destroyed by the eruption.



Santorini, Figure 7 Stratigraphic sequence of the LBA eruption deposit. Related seismic activity is indicated, as determined from unpublished geologic data at the Akrotiri excavation and elsewhere on the island, with the origin of seismicity indicated as due to the eruption (*V*) or regional tectonic activity (*T*). Aegean ceramic stratigraphy is identified with *EM* Early Minoan, *MM* Middle Minoan, and *LM* Late Minoan period. Preservation of the ancient city at Akrotiri occurred with partial burial by tephra up to the middle of the second major phase (indicated by the brick pattern), whereupon strong lateral pyroclastic flows and surges removed portions of buildings not already buried; additional destruction came with mud and debris flows during the third and fourth phases of the eruption.

Mitigation planning is lacking. Instead, the hazard becomes marketable. With one of the most spectacular landscapes on this planet, and an infamous antiquity in volcanology, archaeology, and mythology, Santorini is a major tourist attraction. Over the past 100 years, the island has seen its traditional economy based on agriculture (barley, tomatoes), replaced first by quarrying of pumice from the LBA eruption (creating an environmental mess on Santorini and throughout the Aegean Sea from huge floating rafts of pumice), and finally taken over today by viniculture and tourism. Nea Kameni island in the middle of the caldera, the site of eruptions during the past 2000 years and likely in the future, has been made a volcanic park managed and protected by the local municipality; it is an impressive effort in sustainability and landscape preservation but with minimal focus on future hazards. Beneath the northern part of the island from 2011 to 2012, an injection of magma at depth occurred that provided precursory indicators of a possible eruption (Newman et al., 2012). While this did not result in effusive activity, new mapping of the caldera seafloor (Sakellariou et al., 2012, and references therein) has disclosed features indicative of continuing volcanicity (Figure 8).

The setting of Santorini provides one of the most dramatic landscapes on earth that attracts huge populations of tourists every year. The combination of volcanic landscape with contemporary Greek culture mixed with the mythology surrounding the ancient Bronze Age disaster creates one of the major attractions on earth. The past is packaged and advertised; potential disasters are dismissed by local inhabitants and visitors. There seems an attitude, as with populations on most active volcanoes, that eruptive activity is marketable rather than threatening. We can suppose that the ancient Cycladians might disagree.



Santorini, Figure 8 Tectonic and geologic map of the Santorini archipelago (Modified and updated from Novikova et al. (2011), with additional data from Nomikou et al. (2013), and Sakellariou et al. (2012)). The position of this volcanic center may be related to the tectonic offset between the Kameni and Kolumbo tectonic lineaments.

Bibliography

Brown, S. K., Crosweller, H. S., Sparks, R. S. J., Cottrell, E., Deligne, N. I., Guerrero, N. O., Hobbs, L., Kiyosugi, K., Loughlin, S. C., Siebert, L., and Takarada, S., 2014. Characterisation of the Quaternary eruption record: analysis of the Large Magnitude Explosive Volcanic Eruptions (LaMEVE) database. *Journal of Applied Volcanology*, **3**, 5. Open access at http://appliedvolc.com/content/3/1/5

Cottrell, E., Gardner, J. E., and Rutherford, M. J., 1999. Petrologic and experimental evidence for the movement and heating of the pre-eruptive Minoan rhyodacite (Santorini, Greece). *Contributions to Mineralogy and Petrology*, **135**(4), 315–331.

Dominey-Howes, D., and Minos-Minopoulos, D., 2004. Perceptions of hazard and risk on Santorini. *Journal of Volcanology and Geothermal Research*, **137**(4), 285–310.

Doumas, C. G., 1983. *Thera. Pompeii of the Ancient Aegean: Excavations at Akrotiri, 1967–79*. London: Thames and Hudson.

Doumas, C. G., 1992. *The Wall-Paintings of Thera*. Athens: The Thera Foundation.

Doumas, C. G., and Papazoglou, L., 1980. Santorini tephra from Rhodes. *Nature*, **287**(5780), 322–324.

Driessen, J., and MacDonald, C. F., 1997. *The Troubled Island: Minoan Crete before and after the Santorini Eruption*. Aegaeum 17. Liège: Université de Liège, Histoire de l'art et archéologie de la Grèce antique.

Druitt, T. H., 2014. New insights into the initiation and venting of the Bronze-Age eruption of Santorini (Greece), from component analysis. *Bulletin of Volcanology*, **76**(2), article 794. doi:10.1007/s00445-014-0794-x.

Druitt, T. H., and Francaviglia, F., 1990. An ancient caldera cliff line at Phira, and its significance for the topography and geology of pre-Minoan Santorini. In Hardy, D. A. (ed.), *Thera and The Aegean World III: Proceedings of the Third International Congress, Santorini, Greece, 3–9 September 1989, vol. 2: Earth Sciences*. London: The Thera Foundation, pp. 362–369.

Druitt, T. H., and Francaviglia, V., 1992. Caldera formation on Santorini and the physiogeography of the islands in the Late Bronze Age. *Bulletin of Volcanology*, **54**(6), 484–493.

Druitt, T. H., Edwards, L., Mellors, R. M., Pyle, D. M., Sparks, R. S. J., Lanphere, M., Davies, M., and Barriero, B., 1999. *Santorini Volcano*. London: The Geological Society. Geological Society Memoir, Vol. 19.

Eriksen, U., Friedrich, W. L., Buchardt, B., Tauber, H., and Thomsen, M. S., 1990. The Stronghyle caldera: Geological, paleontological and stable isotope evidence from Santorini. In Hardy, D. A. (ed.), *Thera and The Aegean World III: Proceedings of the Third International Congress, Santorini, Greece, 3–9 September 1989, vol. 2: Earth Sciences*. London: The Thera Foundation, pp. 139–150.

Faccenna, C., Becker, T. W., Auer, L., Billi, A., Boschi, L., Brun, J. P., Capitanio, F. A., Funiciello, F., Horváth, F., Jolivet, L., Piromallo, C., Royden, L., Rossetti, F., and Serpelloni, E., 2014. Mantle dynamics in the Mediterranean. *Review of Geophysics*, **52**(3), 283–332, doi:10.1002/2013RG000444.

Friedrich, W. L., 2000. *Fire in the Sea. The Santorini Volcano: Natural History and the Legend of Atlantis*. Cambridge: Cambridge University Press.

Friedrich, W. L., Kromer, B., Friedrich, M., Heinemeier, J., Pfeiffer, T., and Talamo, S., 2006. Santorini eruption radiocarbon dated 1627–1600 B.C. *Science*, **312**(5773), 548.

Jellinek, A. M., and DePaolo, D. J., 2003. A model of the origin of large silicic magma chambers: precursors of caldera-forming eruptions. *Bulletin of Volcanology*, **65**(5), 363–381, doi:10.1007/s00445-003-0277-y.

Johnston, E. N., Phillips, J. C., Bonadonna, C., and Watson, I. M., 2012. Reconstructing the tephra dispersal pattern from the Bronze Age eruption of Santorini using an advection–diffusion model. *Bulletin of Volcanology*, **74**(6), 1485–1507, doi:10.1007/s00445-012-0609-x.

Johnston, E. N., Sparks, R. S. J., Phillips, J. C., and Carey, S., 2014. Revised estimates for the volume of the Late Bronze Age Minoan eruption, Santorini, Greece. *Journal of the Geological Society, London*, **171**(4), 583–590.

Keller, J., Gertisser, R., Reusser, E., and Dietrich, V., 2014. Pumice deposits of the Santorini Lower Pumice 2 eruption on Anafi Island: indications of a Plinian event of exceptional magnitude. *Journal of Volcanology and Geothermal Research*, **278–279**, 120–128.

Manning, S. W., Bronk Ramsey, C., Kutschera, W., Higham, T., Kromer, B., Steier, P., and Wild, E. M., 2006. Chronology for the Aegean Late Bronze Age 1700–1400 B.C. *Science*, **312**(5773), 565–569.

Marinatos, S., 1939. The volcanic destruction of Minoan crete. *Antiquity*, **13**(52), 425–439.

McCoy, F. W., 2009. The eruption within the debate about the date. In Warburton, D. A. (ed.), *Time's Up! Dating the Minoan Eruption of Santorini: Acts of the Minoan Eruption Chronology Workshop, Sandbjerg November 2007*. Athens: Danish Institute at Athens. Danish Institute at Athens Monograph, Vol. 10, pp. 73–90.

McCoy, F. W., and Dunn, S., 2002. Modelling the climatic effects of the LBA eruption of Thera: New calculations of tephra volumes may suggest a significantly larger eruption than previously reported. In *Proceedings, Chapman Conference on Volcanism and the Earth's Atmosphere, Santorini, Greece, June 17–21, 2002*. American Geophysical Union, pp. 21–22.

McCoy, F., and Heiken, G., 2000. The Late-Bronze Age explosive eruption of Thera (Santorini), Greece: regional and local effects. In McCoy, F. W., and Heiken, G. (eds.), *Volcanic Hazards and Disasters in Human Antiquity*. Boulder: Geological Society America. GSA Special Paper, Vol. 345, pp. 43–70.

Newhall, C. G., and Self, S., 1982. The Volcanic Explositivity Index (VEI): an estimate of explosive magnitude for historical volcanism. *Journal of Geophysical Research: Oceans (1978–2012)*, **87**(C2), 1231–1238, doi:10.1029/JC87iC02p01231.

Newman, A. V., Stiros, S., Feng, L., Psimoulis, P., Moschas, F., Saltogianni, V., Jiang, Y., Papazachos, C., Panagiotopoulos, D., Karagianni, E., and Vamvakaris, D., 2012. Recent geodetic unrest at Santorini caldera, Greece. *Geophysical Research Letters*, **39**(6), LO6309, doi:10.1029/2012GL051286.

Nomikou, P., Papanikolaou, D., Alexandri, M., Sakellariou, D., and Rousakis, G., 2013. Submarine volcanoes along the Aegean volcanic arc. *Tectonophysics*, **597–598**, 123–146.

Novikova, T., Papadopoulos, G., and McCoy, F. W., 2011. Modeling of tsunami generated by the giant Late Bronze Age eruption of Thera, south Aegean Sea, Greece. *Geophysical Journal International*, **186**(2), 665–680, doi:10.1111/j.1365-246X.2011.05062.x.

Panagiotakopulu, E., Higham, T., Sarpaki, A., Buckland, P., and Doumas, C., 2013. Ancient pests: the season of the Santorini Minoan volcanic eruption and a date from insect chitin. *Naturwissenschaften*, **100**(7), 683–689, doi:10.1007/s00114-013-1068-8.

Parks, M. M., Biggs, J., England, P., Mather, T. A., Nomikou, P., Palamartchouk, K., Papanikolaou, X., Paradissis, D., Parsons, B., Pyle, D. M., Raptakis, C., and Zacharis, V., 2012. Evolution of Santorini volcano dominated by episodic and rapid fluxes of melt from depth. *Nature Geoscience*, **5**, 749–754.

Pfeiffer, T., 2001. Vent development during the Minoan eruption (1640 BC) of Santorini, Greece, as suggested by ballistic blocks. *Journal of Volcanism and Geothermal Research*, **106**(3–4), 229–242.

Royden, L. H., and Papanikolaou, D. J., 2011. Slab segmentation and late Cenozoic disruption of the Hellenic arc. *Geochemistry, Geophysics, Geosystems*, **12**(3), Q03010. doi:10.1029/2010GC003280.

Sakellariou, D., Rousakis, G., Sigurdsson, H., Nomikou, P., Croff Bell, K. L., and Carey, S., 2012. Seismic stratigraphy of Santorini's caldera: a contribution to the understanding of the Minoan eruption. In *10th Hellenic Symposium on Oceanography and Fisheries*, 7–11 May, 2012.

Sewell, D. A., 2001. *Earth, Air, Fire and Water: An Elemental Analysis of the Minoan Eruption of Santorini Volcano in the Late Bronze Age*. PhD dissertation, University of Reading.

Warburton, D. A. (ed.), 2009. *Time's Up! Dating the Minoan Eruption of Santorini: Acts of the Minoan Eruption Chronology Workshop, Sandbjerg November 2007*. Athens: Danish Institute at Athens. Danish Institute at Athens Monograph, Vol. 10.

Warren, P., and Hankey, V., 1989. *Aegean Bronze Age Chronology*. Bedminster: Bristol Classical Press.

Wiener, M., 2007. Times change: the current state of the debate in Old World Archaeology. In Bietak, M., and Czerny, E. (eds.), *The Synchronisation of Civilisations in the Eastern Mediterranean in the Second Millennium B.C., III: Proceedings of the SCIEM 2000 – 2nd EuroConference, Vienna, 28th of May–1st of June 2003*. Vienna: Österreichischen Akademie der Wissenschaften, pp. 25–47.

Cross-references

Pompeii and Herculaneum
Radiocarbon Dating
Tephrochronology
Tsunamis
Volcanoes and People

SCANNING ELECTRON MICROSCOPY (SEM)

Ellery Frahm
Department of Anthropology, University of Minnesota-Twin Cities, Minneapolis, MN, USA

Definition

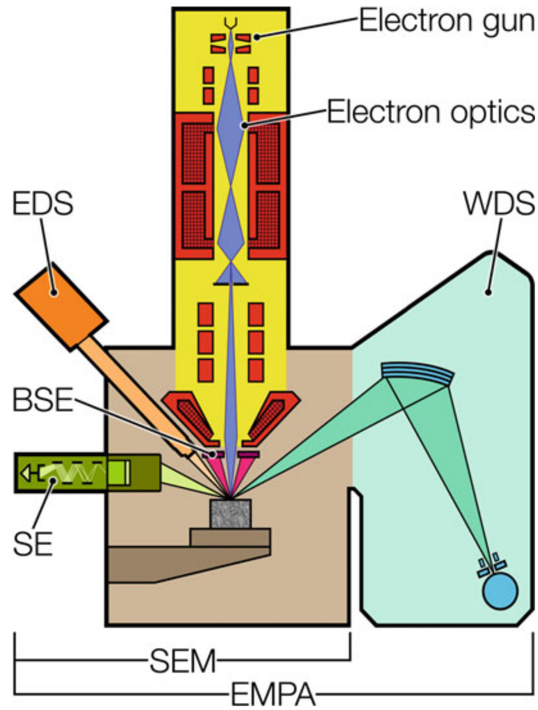
Scanning electron microscopy. A form of microscopy in which a focused beam of accelerated electrons is scanned across the surface of a specimen, generating a number of signals that yield information about its morphology, elemental composition, and, when outfitted with appropriate detectors, crystalline microstructure or other features.

SEM. Scanning electron microscopy or microscope. This acronym is often used interchangeably to describe the imaging/analytical technique and the instrument itself.

SEM in geoarchaeology

Introduction

SEM is a highly versatile imaging and microanalytical technique that has been used throughout the archaeological sciences for almost five decades (e.g., Pilcher, 1968; Brothwell, 1969). Most instruments are equipped for two primary functions: imaging (commonly at high magnifications) and providing compositional (i.e., elemental) information. Instruments can also be outfitted with detectors that offer additional information, such as the crystalline microstructure and orientation of a specimen. Hence, SEM has been frequently used in geoarchaeology whenever a researcher wishes to observe magnified images of a specimen and/or establish its elemental composition on a microscopic scale. Electron microprobe analysis (EMPA; sometimes known as electron probe microanalysis, EPMA) developed alongside SEM and is a closely related technique for electron imaging and X-ray microanalysis. These two techniques essentially exist on an analytical continuum, and their capabilities considerably, and increasingly with time, overlap. Figure 1 illustrates the principal systems of SEM and EMPA.

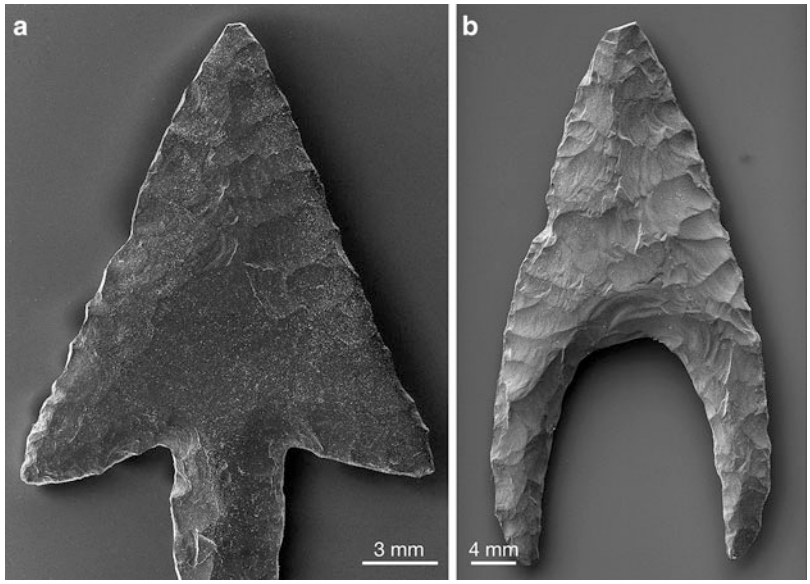


Scanning Electron Microscopy (SEM), Figure 1 Simplified cross-section of a typical scanning electron microscope (*SEM*) and electron microprobe analyzer (*EMPA*). A beam of energetic electrons is produced by the electron gun and focused by an optical system (composed of a series of lenses and apertures) onto a specimen. The primary detectors are shown: a secondary-electron (*SE*) detector, a backscattered-electron (*BSE*) detector, and an energy-dispersive spectrometer (*EDS*) for X-rays. Additionally, EMPAs measure X-rays using a number (typically five) of wavelength-dispersive spectrometers (*WDS*). Not shown are detectors that only certain instruments have (e.g., electron backscatter diffraction or EBSD) (Image by the author).

SEM enables high-magnification imaging of a specimen, and the magnification range with SEM is much greater than that with visible-light microscopy (VLM), from as low as 5× (equivalent to a hand lens) to as high as 200,000× (about two orders of magnitude higher than a petrographic microscope) or even more. In addition, SEM has a superior depth of field (about 300 times better than VLM), which means that the full height of a specimen can appear focused (Figure 2). Most SEMs can also quantitatively or semiquantitatively measure elemental composition based on the X-rays emitted by a specimen under energetic electron bombardment.

SEM fundamentals

An "electron gun" atop the instrument (Figure 1) creates a beam of electrons either via heating (thermionic emission) or electric fields (field emission) and accelerates them toward a specimen. A column of apertures and electromagnetic lenses focus the electron beam onto the



Scanning Electron Microscopy (SEM), Figure 2 SE images of (**a**) a Neolithic stemmed chert point from the Arabian Peninsula and (**b**) a Neolithic hollow-base chert point from Egypt. The greater depth of field for SEM (relative to conventional visible-light microscopy) means that each projectile point appears in focus, not just its edge or topmost surface (Images by the author).

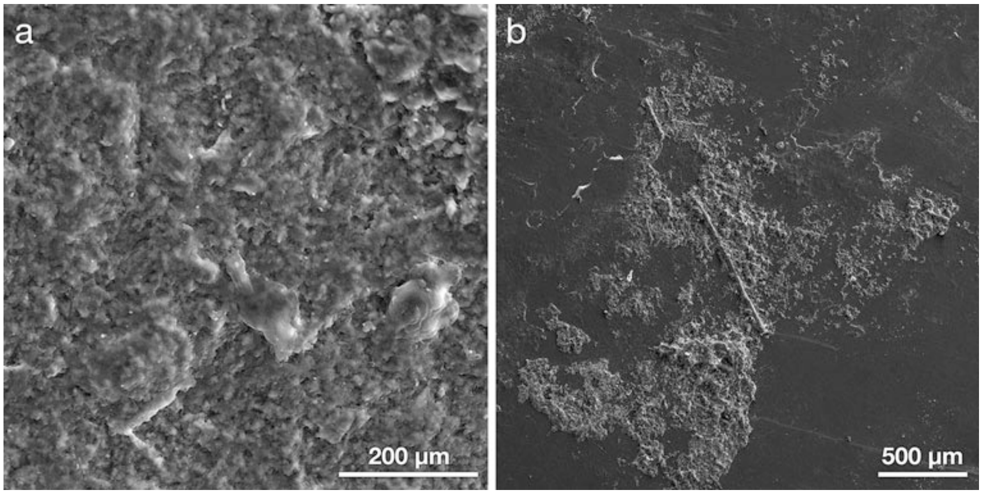
surface of the specimen. To produce an image, the beam quickly scans across the surface, very much like an old CRT-based monitor or television. This process often occurs under high vacuum to reduce scattering of the electrons by air molecules and other undesirable effects. A fairly recent development, though, is imaging at pressures closer to atmosphere, generally called environmental SEM (ESEM), but a number of manufacturer-specific terms have also been introduced (e.g., variable-pressure SEM, low-vacuum SEM, wet SEM). The main advantage is that additional air inside the chamber prevents an electric charge from building up on nonconductive specimens. With the chamber under vacuum, it is necessary to coat specimens with an ultrathin layer (about 100 Å thick) of conductive carbon or gold to prevent the charge buildup from disrupting the imaging. The layer can subsequently be removed if needed, but the use of ESEM eliminates the coating procedure.

When the accelerated electrons strike a specimen, a variety of signals is generated. Some signals are used for imaging, while others are useful for compositional or microstructural analyses when an instrument is outfitted with appropriate detectors. One of the two principal imaging signals is secondary-electron (SE) emission. Low-energy SEs escape from only the outer few nanometers of a specimen's surface. Therefore, they are most sensitive to specimen topography and useful for imaging surface details (Figure 3). SE images are the stereotypical SEM-type images, and many people have seen such images of insects, salt crystals, or pollen as examples.

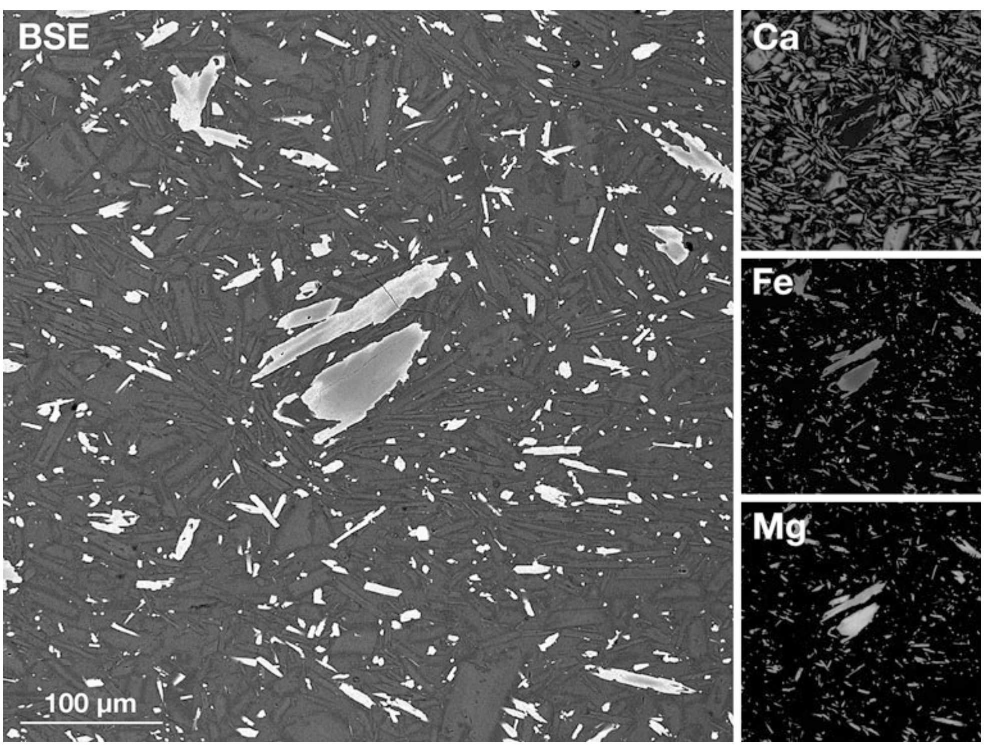
The other principal imaging signal is backscattered-electron (BSE) emission. BSEs are energetic beam electrons that have been deflected back out of a specimen and, as a result of energies much higher than SEs, are less influenced by surface topography. Instead, they are strongly affected by the elemental composition of the specimen: elements with higher atomic numbers deflect back a higher proportion of BSEs. This phenomenon is used to produce images that have compositional contrast (although there is still a topographic component for non-flat specimens). The resulting BSE images exhibit bright regions where the mean atomic number of the specimen is higher and dark regions where it is lower (Figure 4). Contrast in such images reveals relative differences in composition, not the actual elements or their concentrations.

Identifying elements involves measuring the electron-induced X-ray emissions from a specimen. Characteristic X-rays have energies (and, therefore, wavelengths) indicative of the elements from which they are emitted, and their intensities (i.e., the number of X-rays emitted) reflect the concentration of each element. Thus, X-ray spectrometers can reveal a specimen's composition. A modern SEM is typically outfitted with an energy-dispersive spectrometer (EDS; sometimes abbreviated as EDX, EDXA, or the trade name EDAX) to measure these X-rays. Thus, SEM-EDS measures characteristic X-rays at energies that correspond to elements in the specimen, and their intensities can be converted into quantitative elemental abundances. Individual analyses are short, frequently requiring less than a minute or two to measure the X-ray spectrum.

These same characteristic X-rays are measured somewhat differently in EMPA. A microprobe is outfitted with several (usually five) wavelength-dispersive spectrometers (WDS). EMPA discerns X-rays by wavelength,



Scanning Electron Microscopy (SEM), Figure 3 SE images of (**a**) the surface of a Mousterian (i.e., a Middle Paleolithic lithic industry associated with Neanderthals) chert tool from France and (**b**) residue adhering to the surface of an obsidian artifact from Syria. Residues on stone tools have been a recent focus of study with SEM to determine the tools' uses (e.g., Monnier et al., 2012, 2013; Borel et al., 2014) (Images by the author).



Scanning Electron Microscopy (SEM), Figure 4 BSE image and element maps of sanukite, a fine-grained andesitic volcanic rock from the Okayama region of western Japan, where it was intensively used alongside obsidian during the Paleolithic to craft stone tools. The SEM enables examination and elemental analyses of the rock's different minerals, including the enstatite-ferrosilite [$(Mg,Fe)SiO_3$] series pyroxenes in the middle of the images (i.e., bright areas in the Mg and Fe element maps and dark areas in the Ca map) (Images by the author).

instead of energy, for more precise and sensitive measurements. Each analysis is reasonably short, requiring only a few minutes in many instances. Additionally, these instruments are equipped with EDS and can acquire magnified images of a specimen (although the maximum practical magnification is commonly lower than that of SEM).

SEM-EDS is often considered a spot analytical technique. The electron beam is focused on a spot or small area (typically a few micrometers to several millimeters in diameter), and a specimen's composition is measured for the area beneath the electron beam, rather than the entire specimen. Consequently, a researcher can acquire highly localized compositional data, analyze specimens too small to be studied using other techniques, or measure elemental variation across the surface. Therefore, SEM-EDS is well suited to studying mixtures (e.g., different minerals that compose a rock), and a high-resolution array of X-ray measurements permits researchers to map differences in elemental concentrations across the surface of a specimen (Figure 5).

SEM-EDS can also be considered a nondestructive technique in that it does not alter or destroy a specimen, which may be repeatedly analyzed. Specimens, however, must be small enough to fit inside the instrument. Typical maximum dimensions for specimen chambers are ordinarily about 10 cm horizontally and 5 cm vertically. Certain instruments, though, can accept larger specimens. For instance, the Mira-X, owned by the United States Air Force, is the world's largest SEM. With its 3.5 m^3 chamber, the Mira-X was used to examine a 1.8-m-tall terra-cotta warrior from Emperor Qin Shi Huang's mausoleum. Echlin (2009) details various specimen preparation methods for SEM.

Quantitative elemental analysis with SEM-EDS (and EMPA), like most analytical techniques, is comparative. It entails measurement of X-rays from a specimen as well as reference standards, the compositions of which are well known. For each element, one measures X-rays emitted by a standard and those emitted by the specimen, and software calculates the ratio between them and corrects the measurements for various phenomena (e.g., reabsorption of X-rays by other atoms in the material) to calculate a specimen's composition accurately. In the past, such corrections used either empirically derived coefficients or calibration curves based on a number of standards, but these approaches are outdated. Instead, modern software and faster computers use physics-based models to calculate and apply corrections directly to raw data instantaneously.

SEMs have diverse capabilities and configurations. It would be remiss, however, to overlook the importance of an analyst's choices and savoir faire as factors in instrument performance and the resulting images or analytical data (e.g., Goldstein et al., 1981). Long (1995: 15) explains that "these are determined not only by the design of the instrument but also by the expertise of the operator in choosing and setting the optimum operating conditions." Reed (2005: 137) similarly notes: "It is difficult even for an experienced operator to arrive at optimal choices for all the relevant parameters." The considerations governing these choices can fill entire books (e.g., Goldstein et al., 2003; Reed, 2005) and, thus, cannot be explored in detail here. However, it should be appreciated that such choices and practical experience can be significant in SEM (and, especially, EMPA) operation.

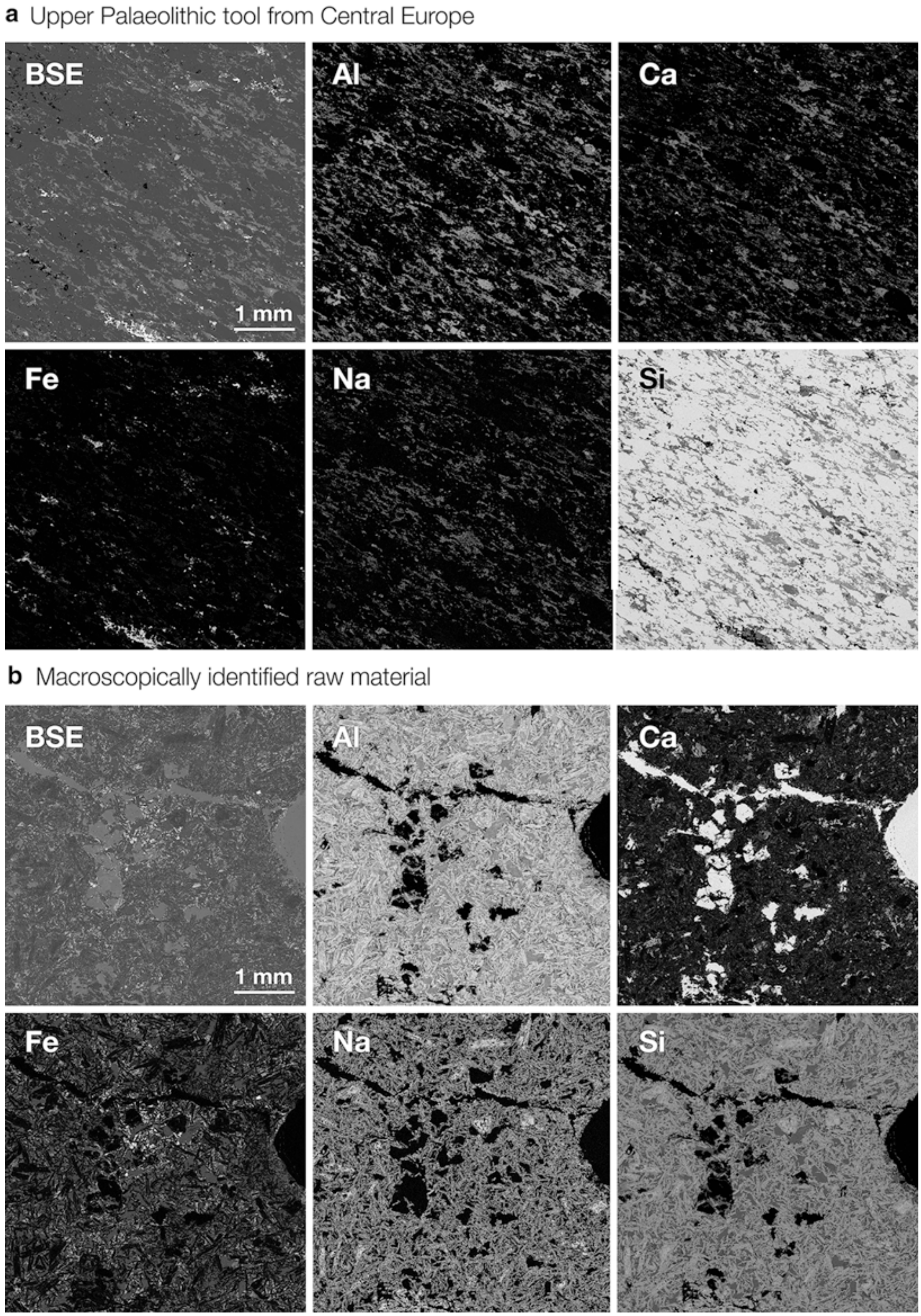
Nevertheless, SEM is more user-friendly than many other analytical techniques and safe enough for students to use. Therefore, it is often incorporated into hands-on exercises in archaeological science courses (e.g., Ponting, 2004; Nicolaysen and Ritterbush, 2005; Hill et al., 2007). Usually low fees also mean that these techniques are broadly accessible to projects without large funding sources, including public and community archaeology projects (Figure 6).

Recent advances

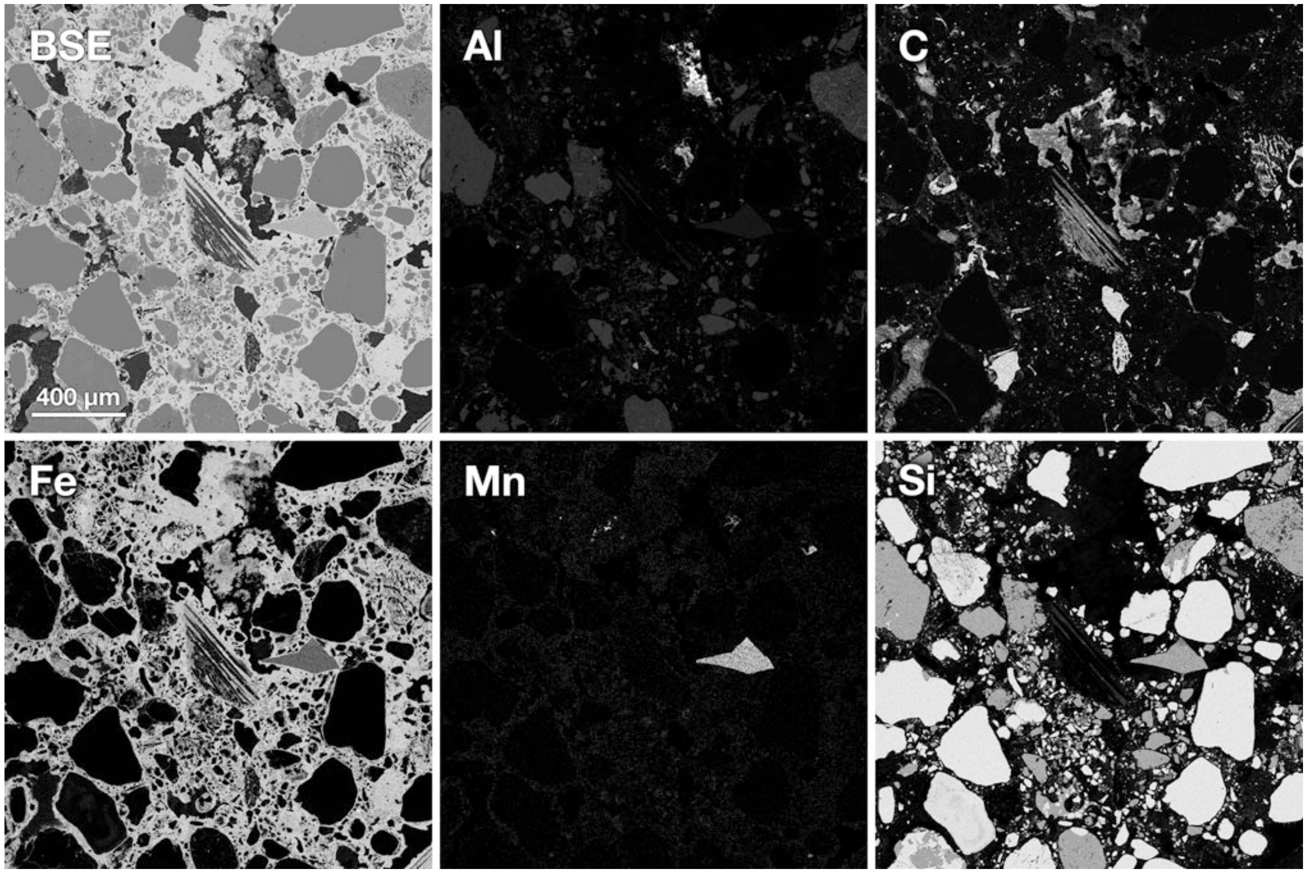
The conference "Scanning Electron Microscopy in Archaeology" was convened at the University of London in 1986, and the proceedings were published 2 years later in a volume edited by Sandra Olsen (1988a), the same year she published a review paper on the same topic in *Advances in Electronics and Electron Physics* (Olsen, 1988b). Most of the instruments in these papers date to the 1970s and early 1980s, but now, nearly three decades later, advances in SEM, especially concerning hardware and data processing, have improved dramatically on early models.

SEMs have seen marked developments since Olsen's publications. For example, the newer type of dedicated BSE detector in a modern SEM yields images superior to those in older papers. SE imaging has also improved due to the development of a new type of electron gun, called a field-emission gun (or FEG), which enables higher-resolution imaging due to an even smaller diameter of the electron beam. With other advances in electron optics, the resolution of a modern research-grade SEM is about 2 nm, a full order of magnitude better than just two decades ago. Digital imaging is another significant advancement. Instead of taking photographs of CRT screens, images are now digitally acquired, stored, and processed. Similarly, the X-ray "dot maps" illustrated in several of those early papers are obsolete, long since replaced by digital X-ray intensity maps.

Furthermore, new detector systems now allow researchers to investigate new problems with SEM. In particular, a system already available on select SEMs detects the beam electrons that diffract out of a specimen due to its crystalline structure and orientation. This phenomenon is called electron backscatter diffraction (EBSD), and it has already been applied in archaeological research (Peruzzo et al., 2011). The main advantage for archaeologists is being able to differentiate in situ minerals with the same elemental composition but distinct crystalline structures and origins. For example, calcite from limestone and aragonite from shell are both chemically calcium carbonate ($CaCO_3$) and indistinguishable with EDS, but EBSD can discriminate between them. In addition, innovative



Scanning Electron Microscopy (SEM), Figure 5 BSE images and X-ray element maps of (**a**) a tool from an Early Upper Paleolithic site in Central Europe and (**b**) a geological specimen from the proposed raw material source based on macroscopic identification. Microscopically, however, the tool and the geological specimen are clearly different. The tool is made of a metamorphosed siliceous (Si-rich) quartzite, conducive to conchoidal fracture. The geological specimen, however, is composed of coarse aluminosilicate minerals and has sizable calcium carbonate veins and inclusions (perhaps filled voids), yielding a material ill-suited to knapping stone tools (Images by the author).



Scanning Electron Microscopy (SEM), Figure 6 During the Elliot Park Neighborhood Archaeology Project, excavations of a nineteenth-century residential neighborhood near downtown Minneapolis turned up slag. BSE imaging and element maps, as shown here, established that the slag was waste from a puddling furnace. This process removes the carbon, silicon, and other impurities from pig iron to produce wrought iron, but there is considerable loss of iron to the slag, resulting in an iron-rich matrix (Images by the author).

X-ray detectors under development combine the speed and ease of EDS with the precision and sensitivity of WDS.

Recent years have seen the introduction of so-called "tabletop" SEMs by several manufacturers. At present, these instruments do not produce results at the highest "research grade," but their advantages include lower purchase and maintenance costs, smaller space requirements, and relative portability, making them attractive for many archaeological applications. The trade-off is that their capabilities are limited (e.g., restricted magnification, sometimes absent EDS), and they vary by model. Their performance, however, will certainly improve in coming years. Eventually, most likely soon, it will become easier and cheaper for archaeologists to bring portable SEMs into the field, therefore making it unnecessary to export artifacts to distant microscopy facilities.

Geoarchaeological applications

SEM and the closely related EMPA have been applied in all subsets of geoarchaeology: soils and sediments, paleoenvironmental research (e.g., microfossils, pollen, phytoliths), raw materials and geological resources (e.g., stones, clays, metal ores, mineral pigments), site formation processes (e.g., sediment micromorphology, erosion), geochronology, and more.

These techniques are commonly applied in sediment micromorphology and microstratigraphy. Courty et al. (2012) used SEM-EDS to find evidence of combustion features in microfacies at the site of Abric Romani in Spain, attesting to Neanderthal pyrotechnology. Similarly, Goldberg et al. (2012) examined the micromorphology of combustion features at two Neanderthal sites in southern France, Pech de l'Azé IV and Roc de Marsal. Karkanas (2002) also used SEM-EDS for micromorphological investigations at several Greek cave sites to link environmental changes and human habitation. Schiegl et al. (2003) were able to discern fireplaces and dumping areas at Upper Paleolithic Hohle Fels cave in Germany with SEM and EMPA, while Mallol et al. (2009) studied site formation processes at a Late Pleistocene rock-shelter in

Uzbekistan. Goldberg and Sherwood (2006) summarize how micromorphologists use cave sediments to elucidate prehistory.

Paleoenvironmental and paleoecological studies often exploit the imaging capacities of SEM. In fact, identifying pollen was one of its earliest archaeological applications (Pilcher, 1968), and it continues to be of great value for that purpose. For example, Lee et al. (2004) used SEM to examine pollen from Canadian wetlands as a means to explore habitation and wild rice exploitation in the region. Similarly, phytoliths (microscopic siliceous plant remains) are frequently examined with SEM. Based on phytoliths recovered from sediments inside Amud Cave, Madella et al. (2002) investigated Levantine Neanderthals' use of plant resources, such as herbaceous plants used as bedding, food, and possibly fuel.

Other botanical remains also yield environmental information. Messager et al. (2008) used SEM to examine fossil fruit remains at the site of Dmanisi in the Georgian Republic and established, based on the taxa present, that the environment was arid. Similarly, Cartwright (2013) identified wood charcoal at the site of Diepkloof rockshelter in Western Cape, South Africa, as a means to study the environment, ecological change, and the use of plant resources during the Middle Stone Age. Likewise, Gómez-Orellana et al. (2014) applied SEM to the examination of charcoal, pollen, and other botanical remains to reconstruct coastal, vegetation, and other ecological changes in a Portuguese river estuary and adjacent archaeological sites.

Another common use of these techniques is identifying minerals used as pigments, including pigments apparently used by Neanderthals. For example, SEM-EDS was one of the tools used by d'Errico et al. (2010) and Salomon et al. (2012) to study the various pigments from Middle Paleolithic strata of Es-Skhul, one of the Mount Carmel caves, and similarly, Dayet et al. (2014) identified the different pigments found at Châtelperronian sites in France. Similar SEM-based studies of Paleolithic pigments include Iriarte et al. (2009) at two cave sites in Spain.

Just as petrologists frequently use SEM-EDS and EMPA to characterize rocks and their mineral components, so, too, do archaeologists. These techniques are often used in petrographic studies of a broad variety of stone artifacts. For example, Tripati et al. (2010) established that stone anchors recovered from shipwrecks off the western Indian coast were made of igneous and sedimentary rocks that occur together in the Rajasthan region using SEM-EDS. Virtually every kind of stone artifact has been investigated with these techniques.

Geochronologists often rely on these techniques in tephrochronology to analyze tiny volcanic glass shards and chemically match them to a specific eruption as a means of correlating strata at sites across an entire region (i.e., areas where the volcanic ash fell). For example, Tryon et al. (2009) produced a chronostratigraphic framework for Paleolithic sites in volcano-rich central Turkey based on EMPA analysis of tephra, enabling more detailed studies of spatial and temporal variation in hominin behavior throughout the region. Sulpizio et al. (2010) used SEM-EDS of tephra layers from lake cores in the Balkans to link them to the same layers found throughout the Central Mediterranean. Researchers in Oxford's Research Laboratory for Archaeology and the History of Art (RLAHA) and the Royal Holloway and Oxford Tephrochronology Research Group (RHOXTOR) routinely pursue SEM-EDS and EMPA analysis of tephras from archaeological sites around the world (e.g., Lane et al., 2011; Lowe et al., 2012; Douka et al., 2014; Lane et al., 2014).

Given the widespread application of SEM-EDS and EMPA to analyze tephra, it is not surprising that these techniques are also helpful in studying obsidian. After early endeavors with the SEM-EDS (e.g., Biró and Pozsgai, 1984; Biró et al., 1986; Keller and Seifried, 1990) and EMPA (e.g., Merrick and Brown, 1984; Merrick et al., 1994; Tykot, 1997), archaeologists have returned to these techniques for obsidian sourcing, that is, geochemically matching obsidian artifacts to their volcanic origins to identify where the raw material was procured. Due to recent advances, obsidian sourcing in the Old World has become highly successful with SEM-EDS (e.g., Acquafredda and Muntoni, 2008; Lugliè et al., 2008; Mulazzani et al., 2010; Poupeau et al., 2010; Reepmeyer et al., 2011; Orange et al., 2013) and EMPA (e.g., Frahm, 2010; Sanna et al., 2010; Nash et al., 2011; Frahm, 2012a, b; Brown et al., 2013; Frahm and Feinberg, 2013a, b; Summerhayes et al., 2014).

Ultimately, the full range of SEM applications is extremely diverse. McLaren (2004) employed SEM to study calcrete deposits that infill paleochannels of the Wadi Dana (Jordan), one of which was associated with a Middle Paleolithic biface, to reconstruct their development and distribution. Van Hoesen and Arriaza (2011) used SEM-EDS to analyze clays used in the mummification of Chilean mummies, whereas Pirrie et al. (2014) investigated the mineral assemblages of soil samples reportedly associated with artifacts as a means to authenticate their contexts. Bello et al. (2013) used SEM-EDS to recognize small chert flakes embedded in antler hammers used in knapping experiments, and Eren et al. (2014) quantified differences in lithic raw material quality and its effects on variation in stone tool shape. A wide variety of applications is also discussed in Weiner's (2010) book *Microarchaeology: Beyond the Visible Archaeological Record*.

Further reading

In-depth considerations of electron and X-ray physics are beyond the scope of this entry. Details regarding electron orbitals, ionization energies, and absorption cross-sections have been avoided deliberately. Here, it is simply accepted that the electron beam generates characteristic X-rays. In *The Quantum Dice*, Ponomarev (1993) proposes that "physics is a vast country with a rich and deep culture" (13), drawing an analogy amenable to archaeologists. He maintains that if one does not "get acquainted with the customs and culture" of the physics involving a particular phenomenon, one will only "know as much about it as tourists know about an unfamiliar country whose culture is foreign to them and whose language they do not understand" (13). Admittedly, readers are left here at what Ponomarev (1993) sees as the level of "bright neon signs and posters" (13). Those interested in greater detail regarding the physics of SEM and EMPA are forwarded to Goldstein et al. (2003) and Reed (2005). Unfortunately, these largely application-focused books are about a decade old and, in turn, increasingly do not reflect the current state of the art. As of this writing, however, there is a lack of newer, geoarchaeologically relevant texts.

Summary

SEM is among the most versatile techniques in geoarchaeology, and it is well suited to studies of a broad range of artifacts as well as archaeological and geological materials. Just a few of the applications could be introduced here. These instruments are routinely used to acquire magnified images of a specimen (SE images) and study elemental compositions and their spatial variation (BSE images and X-rays measured with EDS and/or WDS). Common applications, therefore, include examination of small objects or features, identifying different components of a specimen or mixture, and measuring a specimen's elemental composition and/or structure quantitatively. The instruments are widely available at most universities, often in geological departments and/or core analytical facilities, contributing to their frequent use.

Given the proliferation of "tabletop" SEMs, it will eventually become easier and cheaper to bring such portable instruments into the field rather than send artifacts or geological specimens to distant microscopy facilities. It will also be much faster. For example, stone tools could be examined for residues in a field lab shortly after their excavation, not months or years later halfway around the world. By transplanting such observations to a field context instead of a laboratory one, portable SEM instruments become a facilitating technology for geoarchaeology, minimizing physical and temporal barriers that have often segregated such research between distant places and often lengthy intervals. This portability can unite field- and laboratory-based activities within a shared setting. SEM observations, previously available only after artifacts or specimens have been long separated from their contexts, can now be made locally, providing rapid feedback while researchers are still actively excavating.

Bibliography

Acquafredda, P., and Muntoni, I. M., 2008. Obsidian from Pulo di Molfetta (Bari, Southern Italy): provenance from Lipari and first recognition of a Neolithic sample from Monte Arci (Sardinia). *Journal of Archaeological Science*, **35**(4), 947–955.

Bello, S. M., Parfitt, S. A., De Groote, I., and Kennaway, G., 2013. Investigating experimental knapping damage on an antler hammer: a pilot-study using high-resolution imaging and analytical techniques. *Journal of Archaeological Science*, **40**(12), 4528–4537.

Biró, K. T., and Pozsgai, I., 1984. Obszidián lelőhely-azonosítás elektronsugaras mikroanalízis segítségével [Obsidian characterization by electron microprobe analysis]. *Iparrégészet [Industrial Archaeology]*, **2**, 25–38 (in Hungarian).

Biró, K. T., Pozsgai, I., and Vladár, A., 1986. Electron beam microanalyses of obsidian samples from geological and archaeological sites. *Acta Archaeologica Academiae Scientiarum Hungaricae*, **38**, 257–278.

Borel, A., Ollé, A., Vergès, J. M., and Sala, R., 2014. Scanning electron and optical light microscopy: two complementary approaches for the understanding and interpretation of usewear and residues on stone tools. *Journal of Archaeological Science*, **48**, 46–59.

Brothwell, D. R., 1969. The study of archaeological materials by means of the scanning electron microscope: an important new field. In Brothwell, D. R., and Higgs, E. S. (eds.), *Science in Archaeology: A Survey of Progress and Research*, 2nd edn. London: Thames & Hudson, pp. 564–566.

Brown, F. H., Nash, B. P., Fernandez, D. P., Merrick, H. V., and Thomas, R. J., 2013. Geochemical composition of source obsidians from Kenya. *Journal of Archaeological Science*, **40**(8), 3233–3251.

Cartwright, C. R., 2013. Identifying the woody resources of Diepkloof Rock Shelter (South Africa) using scanning electron microscopy of the MSA wood charcoal assemblages. *Journal of Archaeological Science*, **40**(9), 3463–3474.

Courty, M.-A., Carbonell, E., Vallverdú Poch, J., and Banerjee, R., 2012. Microstratigraphic and multi-analytical evidence for advanced Neanderthal pyrotechnology at Abric Romani (Capellades, Spain). *Quaternary International*, **247**, 294–312.

d'Errico, F., Salomon, H., Vignaud, C., and Stringer, C., 2010. Pigments from the Middle Palaeolithic levels of Es-Skhul (Mount Carmel, Israel). *Journal of Archaeological Science*, **37**(12), 3099–3110.

Dayet, L., d'Errico, F., and Garcia-Moreno, R., 2014. Searching for consistencies in Châtelperronian pigment use. *Journal of Archaeological Science*, **44**, 180–193.

Douka, K., Jacobs, Z., Lane, C., Grün, R., Farr, L., Hunt, C., Inglis, R. H., Reynolds, T., Albert, P., Aubert, M., Cullen, V. L., Hill, E., Kinsley, L., Roberts, R. G., Tomlinson, E. L., Wulf, S., and Barker, G., 2014. The chronostratigraphy of the Haua Fteah cave (Cyrenaica, northeast Libya). *Journal of Human Evolution*, **66**, 39–63.

Echlin, P., 2009. *Handbook of Sample Preparation for Scanning Electron Microscopy and X-Ray Microanalysis*. New York: Springer.

Eren, M. I., Roos, C. I., Story, B. A., von Cramon-Taubadel, N., and Lycett, S. J., 2014. The role of raw material differences in stone tool shape variation: an experimental assessment. *Journal of Archaeological Science*, **49**, 472–487.

Frahm, E., 2010. *The Bronze-Age Obsidian Industry at Tell Mozan (Ancient Urkesh), Syria*. PhD dissertation, Department of Anthropology, University of Minnesota. Online via the University of Minnesota's Digital Conservancy, http://purl.umn.edu/99753.

Frahm, E., 2012a. Distinguishing Nemrut Dağ and Bingöl A obsidians: geochemical and landscape differences and the archaeological implications. *Journal of Archaeological Science*, **39**(5), 1436–1444.

Frahm, E., 2012b. Non-destructive sourcing of Bronze age near Eastern obsidian artefacts: redeveloping and reassessing electron microprobe analysis for obsidian sourcing. *Archaeometry*, **54**(4), 623–642.

Frahm, E., and Feinberg, J. M., 2013a. Empires and resources: Central Anatolian obsidian at Urkesh (Tell Mozan, Syria) during the Akkadian period. *Journal of Archaeological Science*, **40**(2), 1122–1135.
Frahm, E., and Feinberg, J. M., 2013b. Environment and collapse: Eastern Anatolian obsidians at Urkesh (Tell Mozan, Syria) and the third-millennium Mesopotamian urban crisis. *Journal of Archaeological Science*, **40**(4), 1866–1878.
Goldberg, P., and Sherwood, S. C., 2006. Deciphering human prehistory through the geoarcheological study of cave sediments. *Evolutionary Anthropology*, **15**(1), 20–36.
Goldberg, P., Dibble, H., Berna, F., Sandgathe, D., McPherron, S. J. P., and Turq, A., 2012. New evidence on Neandertal use of fire: examples from Roc de Marsal and Pech de l'Azé IV. *Quaternary International*, **247**, 325–340.
Goldstein, J. I., Newberry, D. E., Echlin, P., Joy, D. C., Fiori, C., and Lifshin, E., 1981. *Scanning Electron Microscopy and X-ray Microanalysis: A Text for Biologists, Materials Scientists, and Geologists*. New York: Plenum Press.
Goldstein, J. I., Newbury, D. E., Joy, D. C., Lyman, C. E., Echlin, P., Lifshin, E., Sawyer, L., and Michael, J. R., 2003. *Scanning Electron Microscopy and X-ray Microanalysis*, 3rd edn. New York: Springer.
Gómez-Orellana, L., Ramil-Rego, P., Badal, E., Carrión Marco, Y., and Muñoz Sobrino, C., 2014. Mid-holocene vegetation dynamics in the Tejo River estuary based on palaeobotanical records from Ponta da Passadeira (Barreiro–Setúbal, Portugal). *Boreas*, **43**(4), 792–806.
Hill, A. D., Lehman, A. H., and Parr, M. L., 2007. Using scanning electron microscopy with energy dispersive X-ray spectroscopy to analyze archaeological materials. Introducing scientific concepts and scientific literacy to students from all disciplines. *Journal of Chemical Education*, **84**(5), 810–813.
Iriarte, E., Foyo, A., Sánchez, M. A., Tomillo, C., and Setién, J., 2009. The origin and geochemical characterization of red ochres from the Tito Bustillo and Monte Castillo Caves (Northern Spain). *Archaeometry*, **51**(2), 231–251.
Karkanas, P., 2002. Micromorphological studies of Greek prehistoric sites: new insights in the interpretation of the archaeological record. *Geoarchaeology*, **17**(3), 237–259.
Keller, J., and Seifried, C., 1990. The present status of obsidian source identification in Anatolia and the Near East. In Albore Livadie, C., and Widemann, F. (eds.), *Volcanology and Archaeology: Proceedings of the European Workshops of Ravello, November 19–27, 1987 and March 30–31, 1989*. Strasbourg: Council of Europe. PACT: Journal of the European Study Group on Physical, Chemical, Biological and Mathematical Techniques Applied to Archaeology 25, pp. 57–87.
Lane, C. S., Blockley, S. P. E., Bronk Ramsey, C., and Lotter, A. F., 2011. Tephrochronology and absolute centennial scale synchronisation of European and Greenland records for the last glacial to interglacial transition: a case study of Soppensee and NGRIP. *Quaternary International*, **246**(1–2), 145–156.
Lane, C. S., Cullen, V. L., White, D., Bramham-Law, C. W. F., and Smith, V. C., 2014. Cryptotephra as a dating and correlation tool in archaeology. *Journal of Archaeological Science*, **42**, 42–50.
Lee, G.-A., Davis, A. M., Smith, D. G., and McAndrews, J. H., 2004. Identifying fossil wild rice (*Zizania*) pollen from Cootes Paradise, Ontario: a new approach using scanning electron microscopy. *Journal of Archaeological Science*, **31**(4), 411–421.
Long, J. V. P., 1995. Microanalysis from 1950 to the 1990s. In Potts, P. J., Bowles, J. F. W., Reed, S. J. B., and Cave, M. R. (eds.), *Microprobe Techniques in the Earth Sciences*. London: Chapman & Hall. Mineralogical Society Series 6, pp. 1–48.
Lowe, J., Barton, N., Blockley, S., Bronk Ramsey, C., Cullen, V. L., Davies, W., Gamble, C., Grant, K., Hardiman, M., Housley, R., Lane, C. S., Lee, S., Lewis, M., MacLeod, A., Menzies, M., Müller, W., Pollard, M., Price, C., Roberts, A. P., Rohling, E. J., Satow, C., Smith, V. C., Stringer, C. B., Tomlinson, E. L., White, D., Albert, P., Arienzo, I., Barker, G., Borić, D., Carandente, A., Civetta, L., Ferrier, C., Guadelli, J.-L., Karkanas, P., Koumouzelis, M., Müller, U. C., Orsi, G., Pross, J., Rosi, M., Shalamanov-Korobar, L., Sirakov, N., and Tzedakis, P. C., 2012. Volcanic ash layers illuminate the resilience of Neanderthals and early modern humans to natural hazards. *Proceedings of the National Academy of Sciences*, **109**(34), 13532–13537.
Lugliè, C., Le Bourdonnec, F.-X., Poupeau, G., Congia, C., Moretto, P., Calligaro, T., Sanna, I., and Dubernet, S., 2008. Obsidians in the Rio Saboccu (Sardinia, Italy) campsite: provenance, reduction and relations with the wider Early Neolithic Tyrrhenian area. *Comptes Rendus-Palevol*, **7**(4), 249–258.
Madella, M., Jones, M. K., Goldberg, P., Goren, Y., and Hovers, E., 2002. The exploitation of plant resources by Neanderthals in Amud Cave (Israel): the evidence from phytolith studies. *Journal of Archaeological Science*, **29**(7), 703–719.
Mallol, C., Mentzer, S. M., and Wrinn, P. J., 2009. A micromorphological and mineralogical study of site formation processes at the Late Pleistocene site of Obi-Rakhmat, Uzbekistan. *Geoarchaeology*, **24**(5), 548–575.
McLaren, S., 2004. Characteristics, evolution and distribution of Quaternary channel calcretes, southern Jordan. *Earth Surface Processes and Landforms*, **29**(12), 1487–1507.
Merrick, H. V., and Brown, F. H., 1984. Rapid chemical characterization of obsidian artifacts by electron microprobe analysis. *Archaeometry*, **26**(2), 230–236.
Merrick, H. V., Brown, F. H., and Nash, B. P., 1994. Use and movement of obsidian in the Early and Middle Stone Ages of Kenya and northern Tanzania. In Childs, S. T. (ed.), *Society, Culture, and Technology in Africa*. Philadelphia: MASCA, University of Pennsylvania Museum of Archaeology and Anthropology. MASCA Research Papers in Science and Archaeology, Supplement to Vol. 11, pp. 29–44.
Messager, E., Lordkipanidze, D., Ferring, C. R., and Deniaux, B., 2008. Fossil fruit identification by SEM investigations, a tool for palaeoenvironmental reconstruction of Dmanisi site, Georgia. *Journal of Archaeological Science*, **35**(10), 2715–2725.
Monnier, G. F., Ladwig, J. L., and Porter, S. T., 2012. Swept under the rug: the problem of unacknowledged ambiguity in lithic residue identification. *Journal of Archaeological Science*, **39**(10), 3284–3300.
Monnier, G. F., Hauck, T. C., Feinberg, J. M., Luo, B., Le Tensorer, J.-M., and Al Sakhel, H., 2013. A multi-analytical methodology of lithic residue analysis applied to Paleolithic tools from Hummal, Syria. *Journal of Archaeological Science*, **40**(10), 3722–3739.
Mulazzani, S., Le Bourdonnec, F.-X., Belhouchet, L., Poupeau, G., Zoughlami, J., Dubernet, S., Tufano, E., Lefrais, Y., and Khedhaier, R., 2010. Obsidian from the Epipalaeolithic and Neolithic eastern Maghreb. A view from the Hergla context (Tunisia). *Journal of Archaeological Science*, **37**(10), 2529–2537.
Nash, B. P., Merrick, H. V., and Brown, F. H., 2011. Obsidian types from Holocene sites around Lake Turkana, and other localities in northern Kenya. *Journal of Archaeological Science*, **38**(6), 1371–1376.
Nicolaysen, K. P., and Ritterbush, L. W., 2005. Critical thinking in geology and archaeology: interpreting scanning electron microscope images of a lithic tool. *Journal of Geoscience Education*, **53**(2), 166–172.
Olsen, S. L., 1988. Applications of scanning electron microscopy in archaeology. *Advances in Electronics and Electron Physics*, **71**, 357–380.

Olsen, S. L. (ed.), 1988a. *Scanning Electron Microscopy in Archaeology*. British Archaeological Reports, International Series 452. Oxford: British Archaeological Reports.
Orange, M., Carter, T., and Le Bourdonnec, F.-X., 2013. Sourcing obsidian from Tell Aswad and Qdeir 1 (Syria) by SEM-EDS and EDXRF: methodological implications. *Comptes Rendus Palevol*, **12**(3), 173–180.
Peruzzo, L., Fenzi, F., and Vigato, P. A., 2011. Electron backscatter diffraction (EBSD): a new technique for the identification of pigments and raw materials in historic glasses and ceramics. *Archaeometry*, **53**(1), 178–193.
Pilcher, J. R., 1968. Some applications of scanning electron microscopy to the study of modern and fossil pollen. *Ulster Journal of Archaeology*, **31**, 87–91. 3rd series.
Pirrie, D., Rollinson, G. K., Andersen, J. C., Wootton, D., and Moorhead, S., 2014. Soil forensics as a tool to test reported artefact find sites. *Journal of Archaeological Science*, **41**, 461–473.
Ponomarev, L. I., 1993. *The Quantum Dice*. Boca Raton: CRC Press.
Ponting, M., 2004. The scanning electron microscope and the archaeologist. *Physics Education*, **39**(2), 166–170.
Poupeau, G., Le Bourdonnec, F.-X., Carter, T., Delerue, S., Shackley, M. S., Barrat, J.-A., Dubernet, S., Moretto, P., Calligaro, T., Milić, M., and Kobayashi, K., 2010. The use of SEM-EDS, PIXE and EDXRF for obsidian provenance studies in the Near East: a case study from Neolithic Çatalhöyük (central Anatolia). *Journal of Archaeological Science*, **37**(11), 2705–2720.
Reed, S. J. B., 2005. *Electron Microprobe Analysis and Scanning Electron Microscopy in Geology*, 2nd edn. Cambridge: Cambridge University Press.
Reepmeyer, C., Spriggs, M., Anggraeni, Lape, P., Neri, L., Ronquillo, W. P., Simanjuntak, T., Summerhayes, G., Tanudirjo, D., and Tiauzon, A., 2011. Obsidian sources and distribution systems in Island Southeast Asia: new results and implications from geochemical research using LA-ICPMS. *Journal of Archaeological Science*, **38**(11), 2995–3005.
Salomon, H., Vignaud, C., Coquinot, Y., Beck, L., Stringer, C., Strivay, D., and d'Errico, F., 2012. Selection and heating of colouring materials in the Mousterian level of es-Skhul (c. 100 000 years BP, Mount Carmel, Israel). *Archaeometry*, **54**(4), 698–722.
Sanna, I., Le Bourdonnec, F.-X., Poupeau, G., and Lugliè, C., 2010. Ossidiane non sarde in Sardegna. Analisi di un rinvenimento subacqueo nel Porto di Cagliari. In Lugliè, C. (ed.), *L'ossidiana del monte Arci nel Mediterraneo: Nuovi apporti sulla diffusione, sui sistemi di produzione e sulla loro cronologia: Atti del 5. Convegno Internazionale (Pau, Italia, 27–29 giugno 2008)*. Ales: Nur, pp. 99–119.
Schiegl, S., Goldberg, P., Pfretzschner, H.-U., and Conard, N. J., 2003. Paleolithic burnt bone horizons from the Swabian Jura: distinguishing between in situ fireplaces and dumping areas. *Geoarchaeology*, **18**(5), 541–565.
Sulpizio, R., Zanchetta, G., D'Orazio, M., Vogel, H., and Wagner, B., 2010. Tephrostratigraphy and tephrochronology of lakes Ohrid and Prespa, Balkans. *Biogeosciences*, **7**(10), 3273–3288.
Summerhayes, G. R., Kennedy, J., Matisoo-Smith, E., Mandui, H., Ambrose, W., Allen, C., Reepmeyer, C., Torrence, R., and Wadra, F., 2014. Lepong: a new obsidian source in the Admiralty Islands, Papua New Guinea. *Geoarchaeology*, **29**(3), 238–248.
Tripati, S., Mudholkar, A., Vora, K. H., Rao, B. R., Gaur, A. S., and Sundaresh, 2010. Geochemical and mineralogical analysis of stone anchors from west coast of India: provenance study using thin sections, XRF, and SEM-EDS. *Journal of Archaeological Science*, **37**(8), 1999–2009.
Tryon, C. A., Logan, M. A. V., Mouralis, D., Kuhn, S., Slimak, L., and Balkan-Atlı, N., 2009. Building a tephrostratigraphic framework for the Paleolithic of Central Anatolia, Turkey. *Journal of Archaeological Science*, **36**(3), 637–652.
Tykot, R. H., 1997. Characterization of the Monte Arci (Sardinia) obsidian sources. *Journal of Archaeological Science*, **24**(5), 467–479.
Van Hoesen, J., and Arriaza, B., 2011. Characterizing the micromorphology of sediments associated with Chinchorro mummification in Arica, Chile using SEM and EDS. *Archaeometry*, **53**(5), 986–995.
Weiner, S., 2010. *Microarchaeology: Beyond the Visible Archaeological Record*. Cambridge: Cambridge University Press.

Cross-references

Archaeomineralogy
Cave Settings
Chronostratigraphy
Electron Spin Resonance (ESR) in Archaeological Context
Geochemical Sourcing
Hearths and Combustion Features
Microstratigraphy
Paleoenvironmental Reconstruction
Petrography
Pigments
Soil Micromorphology

SEDIMENTOLOGY

Katherine A. Adelsberger
Environmental Studies, Douglas and Maria Bayer Chair in Earth Science, Knox College, Galesburg, IL, USA

Definitions

The scientific study of sediment and sedimentary rocks.

The study of material found at the earth's surface and composed of unlithified rock fragments, chemical precipitates, or biogenic matter.

Sedimentology in geoarchaeology

Introduction

Sediments serve as the primary matrix for most archaeological materials (Goldberg and Macphail, 2006), and they are therefore the main focus of much geoarchaeological research. Although the broader earth science definition of sedimentology includes the study and classification of sediments and sedimentary rocks, in many cases geoarchaeology deals almost exclusively with sediment alone due to the unconsolidated sedimentary nature of many late Quaternary geologic settings, the generally loosely deposited materials that make up archaeological sites themselves, and the nature of the questions geoarchaeologists commonly ask. The majority of the sedimentary concepts are the same in both geology and geoarchaeology, but those interested in a review of sedimentary rocks specifically should consult a more typical earth science source (e.g., Middleton, 2003). Sedimentology is considered here as separate from the study of stratigraphy, and therefore, this discussion does not include concepts such as the layering or bedding of sediments or the structures that may develop during the depositional process.

Sediments and sedimentary rocks are found in a wide range of environmental settings created by a variety of depositional mechanisms. Many of these settings (e.g., alluvial, colluvial, eolian, paludal, glacial, and coastal) are covered individually in some detail in the current volume, making a discussion here unnecessary. However, within the context of geoarchaeological studies, anthropogenically deposited sediments and anthropogenic alteration of naturally deposited sediments must also be considered, particularly in cases where intentional movement and deposition of sediment within cultural contexts have occurred. The most relevant sites to consider include those of mound-building or other site construction processes, but differentiating between human deposits and natural sediments is one of the primary purposes of many geoarchaeological studies regardless of the scale of human impact on sedimentary settings.

Methodologically, the inclusion of human influence on sedimentation requires the use of traditional methods of sedimentology within a more complex interpretive context, as additional kinds of influences must be considered within archaeological settings (such as living surfaces, landfills, hearths and combustion features, etc.). Sedimentology in geoarchaeology includes inquiries into the sources of sediments and the erosional processes that produced them as well as attempts to identify the environmental conditions present when they were deposited. For geoarchaeologists, the topic of depositional (or sedimentary) environment is often foremost among many potential research questions, as the depositional setting can serve as the dominant control over sedimentary characteristics and also provide a great deal of information about the context of any archaeological materials recovered from a sedimentary deposit (Stein and Farrand, 2001).

Sediments and sedimentary rocks are traditionally divided into three major categories, which also apply to geoarchaeological sedimentary studies: clastic, chemical, and biogenic. These serve as the primary matrices for the majority of archaeological artifacts, and understanding their characteristics serves as an initial step toward a more detailed interpretation of depositional or cultural context in sedimentary settings.

Clastic sediments

Sediments composed of weathered pieces of preexisting rock, or clasts, are known as clastic sediments. These sediments are classified by a combination of clast size, shape, and sorting, which together can be referred to as the texture of the sediment. Composition is also a common aspect of clastic sedimentary description, as compositional data may allow for interpretations of sediment provenance. These aspects of clastic sediments are generally described in the field as well as in the lab, and together, they serve as a basic description of a clastic deposit.

Size

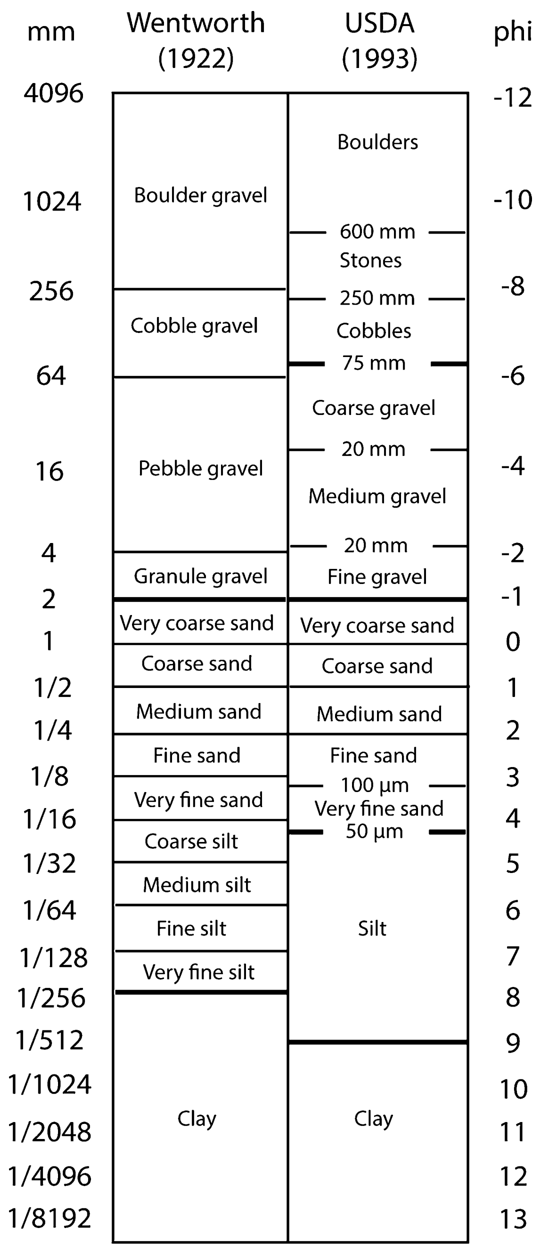
Clast size is determined using one of several scales developed for the purpose of defining the breaks between size categories such as clay, silt, sand, and gravel. Most frequently, sedimentologists utilize the Udden-Wentworth scale (Figure 1), originally proposed by Udden (1898) and further developed by Wentworth (1922). This scale defines breaks between size categories in millimeters. A later addition by Krumbein (1934) provided a unit for the equal distribution of particle size values, known as phi (ϕ), which is calculated using the diameter of a clast in millimeters (d) as

$$\varphi = -\log_2 d \quad (1)$$

The availability of the phi scale allows for better graphical representation of grain size data, among other applications, and is used when quantitatively defining some characteristics of sediments, such as sorting. When working with soils, geoarchaeologists may also use the USDA grain size scale (Soil Conservation Service, 1975; US Division of Soil Survey, 1993), which varies from the Udden-Wentworth scale in the placement of the breaks between particle size categories (Figure 1). Soil scientists also employ terminology unique to soil studies in the use of the word "loam" and the evaluation of texture via a textural triangle where percentages of sand, silt, and clay are used to identify a textural class. Regardless of the scale being used, clast sizes are reported as particle size distributions following laboratory analysis to separate particles into the relevant size categories and to measure distributions as percentages of the overall sample. Although the terms (such as clay, silt, sand, etc., Figure 1) employed by these different scales are the same and are used with the expectation of a general understanding within the geoarchaeological and sedimentological communities, efforts to improve and standardize the size classification system have continued into more recent research (Blott and Pye, 2012), though without significant adoption for practical applications. Laboratory methods for separating and measuring these various size fractions constitute an important component of basic sedimentary analysis in geoarchaeology, as particle size is a fundamental characteristic of sediments, and particle size distribution data can provide keys to depositional interpretations.

Sorting

Sorting refers to the range of particle sizes represented within a sample, which is measured as the standard deviation of clast sizes (Harrell, 1984). These values are computed from grain size values in the phi scale so that ϕ must be attached to the standard deviation values (Boggs, 2006). These standard deviations are also associated with descriptive terms, where a sample containing a wide range of particle sizes is referred to as "poorly



Sedimentology, Figure 1 Comparison of the Wentworth (1922) and USDA Division of Soil Survey (1993) grain size scales (After Blott and Pye, 2012).

sorted" and a sample containing a small range of particle sizes is referred to as "well sorted" (after Folk and Ward, 1957; Folk, 1966, Folk, 1974; Boggs, 2006):

ϕ Standard deviation	Description
<0.35ϕ	Very well sorted
0.35–0.50ϕ	Well sorted
0.50–0.71ϕ	Moderately well sorted
0.71–1.00ϕ	Moderately sorted
1.00–2.00ϕ	Poorly sorted
2.00–4.00ϕ	Very poorly sorted
>4.00ϕ	Extremely poorly sorted

The descriptive terms that correspond to these standard deviation measurements are also often used to describe sediments in the field by following visual guides for estimating sorting (e.g., Harrell, 1984), instead of measuring standard deviations. Although the statistical measurement is preferred for the sake of consistency and clarity, the use of these terms as estimates alone within a field setting provides comparative phrases for field description that can later be verified in a laboratory setting.

Shape

Clast shape is defined as a combination of the form, roundness, and surface texture of particles (Barrett, 1980). The first of these characteristics, *form*, refers to the similarity between the lengths of the three axes of any clast. A clast with similar lengths along all axes has high sphericity (Wadell, 1932), whereas a clast with highly unequal lengths will be elongated along one of them, a form referred to as platy. This idea of sphericity initially laid out by Wadell (1932) was later altered by Krumbein (1941) to define sphericity (ψ) as

$$\psi = \sqrt[3]{\frac{\text{volume of particle}}{\text{volume of circumscribing sphere}}} \qquad (2)$$

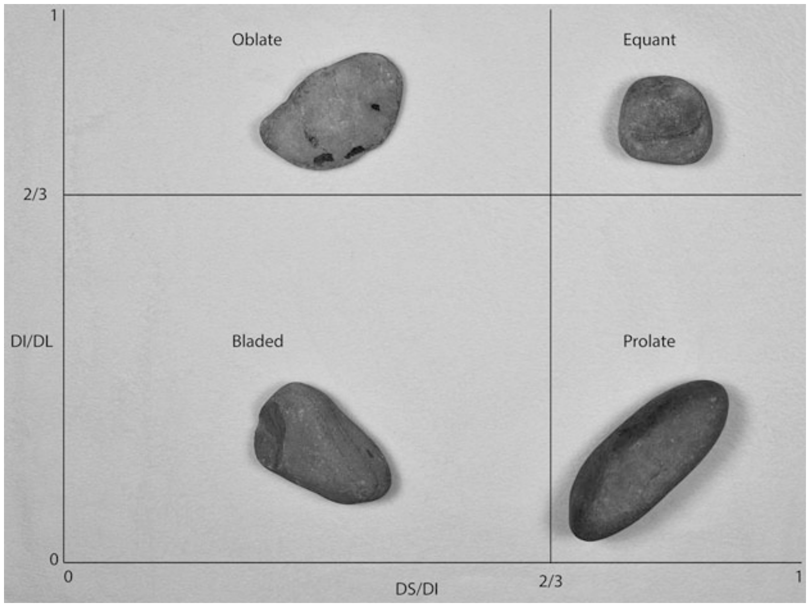
Because any clast with three axes would have three diameters (D) for the long, intermediate, and short axes (D_L, D_I, and D_S, respectively), this can also be expressed using the volume of a sphere, $\pi/6\ D^3$, so that (Boggs, 2006)

$$\psi_I = \sqrt[3]{\frac{\frac{\pi}{6} D_L D_I D_S}{\frac{\pi}{6} D_L^3}} = \sqrt[3]{\frac{D_S D_I}{D_L^2}} \qquad (3)$$

Another way of measuring sphericity was proposed by Sneed and Folk (1958) in order to predict more accurately the behavior of a particle in a fluid, as the sphericity calculation developed by Krumbein (1941) did not produce values that would correspond with clast settling velocity or the orientation of platy clasts due to fluid flow (Boggs, 2001). This alternative sphericity measurement, referred to as maximum projection sphericity (ψ_p), is defined as (Sneed and Folk, 1958)

$$\frac{\text{maximum projection area of a sphere with the same volume as the clast}}{\text{maximum projection area of the clast}}$$

This can also be expressed using the maximum projection area as



Sedimentology, Figure 2 Examples of clast form after Zingg (1935).

$$\psi_p = \sqrt[3]{\frac{D_S^2}{D_L D_I}} \quad (4)$$

Using this definition of sphericity, Sneed and Folk (1958) were able to demonstrate a closer correspondence between sphericity and clast behavior within flowing fluids, but maximum projection sphericity is otherwise not considered to be more valid than the quantification method developed by Krumbein (1941) for describing particle form (Boggs, 2006).

One shortcoming of sphericity measurements is the lack of correspondence between a sphericity value and actual clast shape, regardless of the sphericity measurement that is utilized (Boggs, 2001). In an effort to solve this problem, Zingg (1935) plotted the ratios of the particle axes D_I/D_L versus D_S/D_I in order to categorize particle shapes. In this system, high D_I/D_L values indicate *oblate* (disc-shaped) particles when D_S/D_I is low and *equant* particles when D_S/D_I is high, in which case all axes are approximately the same length. If D_I/D_L is low, particles may be classified as *bladed* when D_S/D_I is low or *prolate* when D_S/D_I is high (Zingg, 1935) (Figure 2). This method of categorization of form is more easily operationalized in the field than other measurements, because these qualitative descriptions can be made upon visual inspection of clasts. Axis ratios can be compared to quantitative sphericity measurements if necessary.

As with particle size, later research was built upon these foundational studies of shape in an attempt to create more functional descriptions of form; these ranged from an attempt to return to a version of Wadell's (1932) original sphericity measurements (Aschenbrenner, 1956) to the development of a more simplified, visually determined method of describing form in the field (Crofts, 1974). Most modern work, however, depends upon the original definitions provided by Wadell (1932) and Sneed and Folk (1958), which can be utilized to examine the role of particle form on laboratory methods (Fernlund, 1998) or on clast transport in different geologic settings (Pizzuto et al., 1999; Larsen and Piotrowski, 2003; Bluck, 2011).

The second component of particle shape is the *roundness* of a clast. This topic was pioneered quantitatively by Wentworth (1919), who used the curvature of the corner of a clast with the largest projection in order to measure roundness. However, most modern work follows Wadell (1932), who separated roundness from form and specified that a spherical particle may have minimal roundness or vice versa. The roundness of a clast, taken as the mean of the sum of the roundness of all the corners of that clast, is known as the Wadell roundness (R_W) (Boggs, 2006), where a radius (r) can be measured for a sphere that fits inside each of a number of corners (N) of a clast, and R is taken as the radius of the largest sphere that can be inscribed within the particle's outline and aligned with the plane being measured (Wadell, 1932). This is expressed as

$$R_W = \frac{\sum \frac{r}{R}}{N} \quad (5)$$

Due to the number of individual measurements required to evaluate the Wadell roundness quantitatively, later work attempted to provide simpler methods of roundness calculation (Russell and Taylor, 1937; Pettijohn, 1949; Dobkins and Folk, 1970). However, the primary alteration to Wadell's work commonly utilized in current field studies was the development of comparative scales that allow for a visual estimation of roundness (Krumbein, 1941), including the terms angular, subangular, subrounded, rounded, and well rounded to describe the smoothness of the angles of a clast (Powers, 1953). Similar to visual estimations of sediment sorting, such methods are much more functional in field settings, as they allow for the practical use of roundness as a characteristic of sedimentary particles in field descriptions.

The final component of clast shape is *surface texture*, which is a term describing the presence of pits, fractures, scratches, or other variations present on the surface of a clast. This method of particle description is primarily laboratory based, as it involves the use of either a petrographic or, in most studies, an electron microscope in order to view surface variations at magnification (Krinsley and Takahashi, 1962; Wolfe, 1967; Krinsley and Doornkamp, 1973). Studies of surface texture may provide evidence of transport and depositional mechanisms within sedimentary contexts (Helland et al., 1997; Timireva and Velichko, 2006; Marshall et al., 2012), and they can therefore be useful in paleoenvironmental work as well as site formation inquiries in geoarchaeology.

Fabric

Fabric refers to the arrangement of clasts within a sedimentary package along with the textural characteristics such as size, shape, and sorting. This concept includes the orientation of clasts as well as how they are spaced, which is known as packing (Boggs, 2001). Grain orientation in clasts with one elongated axis (platy) will preferentially align with the direction of fluid flow, either parallel (Rusnak, 1957; Parkash and Middleton, 1970) or perpendicular to the flow direction (Boggs, 2006; Goldberg and Macphail, 2006). Transported clasts may also display imbrication, where clasts overlap with dips of similar angle while simultaneously displaying orientation according to the current direction (Rusnak, 1957; Byrne, 1963). These features of sediment fabric are primarily found within environments of fluid flow, such as fluvial and colluvial deposits.

The packing of grains determines the porosity, or the amount of void space, within a sediment package, as well as the permeability, which is a measure of the interconnectedness of the void spaces. Poorly sorted sediments generally have lower porosity and permeability because void spaces can be filled by smaller particles, whereas grains of similar size will be limited in their packing (Boggs, 2006). Sorting will also determine whether sediments are *grain supported*, wherein all clasts are in contact with other grains of similar size, or whether the deposits are *matrix supported*, where coarser clasts are not in contact with one another but are instead supported by the surrounding matrix of smaller particles (Goldberg and Macphail, 2006). Concepts such as sorting and clast size are therefore difficult to separate from sediment fabric, as they are controlling factors for fabric characteristics such as grain packing. Fabric may also be relevant to smaller-scale features visible via micromorphology techniques or the structural development of soils, making the concept of fabric more encompassing within geoarchaeological studies than would be the situation in traditional sedimentology.

Composition

Clast composition plays a significant role in the determination of the characteristics described thus far, as lithology will control hardness and resistance to weathering during transport. The composition of clasts will therefore determine the rate at which they break down to smaller particle sizes (Wilson, 2004) as well as the extent to which a grain surface will be scratched or otherwise affected by contact with other geologic materials. For this reason, the majority of clast surface texture analyses are conducted on quartz, which is a more resistant mineral and can be maintained in an environment long enough to accumulate indicative surface textures (e.g., Krinsley and Doornkamp, 1973; Culver et al., 1983). The lithology of clasts found within sedimentary settings can also allow for the identification of the parent rock for a given deposit (Lindsey et al., 2007), providing evidence for transport mechanisms and distances, with the understanding that the original composition may have been altered significantly by differential weathering during transport processes. Finally, the composition of clastic sedimentary deposits may be controlled or altered by the development of precipitate minerals within or around the clasts themselves, which may also serve as cement during lithification.

Chemical sediments

Chemical sediments are the result of precipitation of mineral crystals from solution. From a geoarchaeological standpoint, these sediments are most relevant in the context of lacustrine, paludal, cave, or freshwater environments. The sedimentary deposits that result from the precipitation process are determined primarily by the ions available in solution within the environment of precipitate formation. One common chemical sediment, known as an evaporite, is composed of evaporite minerals such as gypsum and halite, which accumulate as the evaporation of water concentrates ions in solution (Boggs, 2006). Evaporite deposits may provide evidence for climate shifts, and so they are useful in paleoenvironmental studies where their presence makes examination of climate change possible (Renaut and Tiercelin, 1994; Deotare et al., 2004), particularly in arid zones and within the sedimentary records of saline water bodies. Mineral accumulations, especially those resulting from groundwater activity, can also be composed of a variety of other precipitates, such as iron oxides including goethite and jarosite

(Schwertmann et al., 1987; Long et al., 1992; Herbert, 1995; Zheng et al., 2007; Adelsberger and Smith, 2010). This is particularly true in cases where precipitation occurs in acidic conditions, due either to the depositional environment or contamination. In addition to providing evidence for depositional conditions, the nature of these precipitates is controlled by water chemistry, which can be determined largely by aquifer characteristics. In cases where solutions are supersaturated with silica, the precipitation of microcrystalline quartz will lead to the formation of chert, also known as flint, which is important to geoarchaeological work because of the prevalence of this material in early stone tool manufacture (Renfrew and Bahn, 2008). However, the combined geoarchaeological literature on all of these chemical deposits would not match the focus on carbonates, which comprises the most commonly encountered category of chemical sediments utilized in geoarchaeological studies.

Carbonates

Carbonate rocks include any sedimentary rocks composed of carbonate minerals, such as calcite, dolomite, or aragonite. The carbonate-bearing sediments relevant to most archaeological contexts include tufa/travertine and speleothems, all of which result from the deposition of $CaCO_3$ via the degassing of CO_2 from calcite-saturated freshwater, thereby increasing the pH and decreasing the solubility of calcite (Ford and Pedley, 1996; Chen et al., 2004). The terms tufa and travertine may be used interchangeably, with "tufa" more often used to refer to more friable deposits and "travertine" used for harder, crystalline, often layered deposits of calcium carbonate. Historically, the term "travertine" was initially utilized to describe hydrothermal deposits in Italy (Pentecost, 1993); accordingly, some authors continue to separate these terms according to the nature of the water body in question, with tufas originating from ambient-temperature freshwater environments (Sweeting, 1972) and travertines forming in hydrothermal conditions (Ford and Pedley, 1996). However, this is not always the case in the modern literature. Tufas are often described in environments where carbonate-rich surface waters or springs lead to carbonate deposition (Ford and Pedley, 1996; Smith et al., 2004), and although travertines can be described as deposits originating from hydrothermal groundwater sources (e.g., Renaut et al., 2013; Pola et al., 2014), this term may also be used to describe the more general case of freshwater carbonate deposition, particularly within fluvial deposits in karst terrains (e.g., Zhang et al., 2001; Drysdale et al., 2002). Regardless of the terminology used, microbial and plant associations may facilitate carbonate deposition in addition to creating biogenic structures within the resulting sediments (Chen et al., 2004; Pentecost, 2005; de Wet and Davis, 2010).

Cave deposits serve as another potential area of significant carbonate sedimentation from freshwater. The mineralogy of these deposits is often similar to those found in other settings, but they form via the percolation of water through overlying limestone within a karstic terrain and the resultant growth of features such as stalactites and flowstones (Hill and Forti, 1997; Tooth and Fairchild, 2003). In all of these settings, carbonate sediments are useful as potential chronostratigraphic units due to the presence of trace amounts of uranium within the deposits. Carbonates may therefore afford chronologic control within an archaeological site or provide contextual dates on any archaeological materials contained within the sediments themselves (Smith et al., 2007). Carbonates may additionally serve as paleoenvironmental proxies via measurement of Mg/Ca ratios, which serve as a proxy for paleotemperature, as well as through stable isotope measurements on the carbon and oxygen components of $CaCO_3$ (Drummond et al., 1995; Andrews, 2006; Kieniewicz and Smith, 2007; Lojen et al., 2009). Speleothems in particular can serve as paleoclimate proxies over periods of continuous deposition under the right conditions (Lauritzen, 2005; Fairchild et al., 2006). These applications of carbonate sediments make them particularly valuable when they are found within archaeological contexts, as the environmental conditions interpreted via these proxy data would have direct relevance to human activities and landscapes.

Biogenic sediments

Sediments composed of biological materials, such as shell or plant fragments, are known as biogenic sediments. In archaeological contexts, such sediments may include natural accumulations of organic matter such as peat, anthropogenically derived deposits such as shell middens, or plant remains transported into a site. These types of deposit are not relevant to the majority of archaeological contexts, but they can be particularly useful to geoarchaeologists where they are found because they provide unique preservational settings and paleoenvironmental data.

Peat is an accumulation of decomposing vegetation that forms in wetland environments. The organic richness of these deposits allows for chronological control of some sites via carbon 14 dating methods, which can be enhanced by the fact that the reducing conditions present in the catotelm layer of peat bogs provide an opportunity for prolonged preservation of organic matter, including human bodies and wooden artifacts (van den Berg et al., 2010). Peat has also served as an important paleoenvironmental proxy since the early 1900s (Dachnowski, 1922), providing evidence for changes in vegetation via pollen and fossil records (Barber et al., 2003; Blaauw and Mauquoy, 2012) as well as preserving elemental evidence of atmospheric compositions and human influence (Yu et al., 2010).

Shell middens are anthropogenically deposited accumulations of mollusk remains that result from the consumption or ritual use of these organisms at coastal sites. Although anthropogenic in origin, they can still be categorized as sediments because they are collections of biogenic matter, and they are of particular interest to geoarchaeology because they may provide evidence for diet, marine exploitation of resources, settlement patterns, or paleoenvironmental change (Álvarez et al., 2011; Gutiérrez-Zugasti et al., 2011). Because they are human creations, shell middens must be considered only within the context of human activity and may contain significant bias when they are used to interpret anything other than human activity itself; this is not the case for the other sedimentary deposits examined here, but it is a relevant consideration for anthropogenic sedimentary environments examined elsewhere in this volume.

Summary

Sedimentology has been a key component of geological and archaeological studies since the initial development of these fields, and it remains central to the methods employed in answering geoarchaeological questions. Clastic, chemical, and biogenic sediments all serve as matrices for archaeological materials, and they may additionally contribute to the studies of paleoenvironmental conditions and site formation that inform our understanding of human decision-making and behaviors in the past. Recognizing the basic components and applications of sedimentary data collection and analysis is mandatory for the majority of geoarchaeological studies, and sedimentary characteristics will therefore feature prominently in many of the more specific environmental and methodological entries in this volume.

Bibliography

Adelsberger, K. A., and Smith, J. R., 2010. Paleolandscape and paleoenvironmental interpretation of spring-deposited sediments in Dakhleh Oasis, Western Desert of Egypt. *Catena*, **83**(1), 7–22.

Álvarez, M., Godino, I. B., Balbo, A., and Madella, M., 2011. Shell middens as archives of past environments, human dispersal and specialized resource management. *Quaternary International*, **239**(1–2), 1–7.

Andrews, J. E., 2006. Palaeoclimatic records from stable isotopes in riverine tufas: synthesis and review. *Earth-Science Reviews*, **75** (1–4), 85–104.

Aschenbrenner, B. C., 1956. A new method of expressing particle sphericity. *Journal of Sedimentary Petrology*, **26**(1), 15–31.

Barber, K. E., Chambers, F. M., and Maddy, D., 2003. Holocene palaeoclimates from peat stratigraphy: macrofossil proxy climate records from three oceanic raised bogs in England and Ireland. *Quaternary Science Reviews*, **22**(5–7), 521–539.

Barrett, P. J., 1980. The shape of rock particles, a critical review. *Sedimentology*, **27**(3), 291–303.

Blaauw, M., and Mauquoy, D., 2012. Signal and variability within a Holocene peat bog – chronological uncertainties of pollen, macrofossil and fungal proxies. *Review of Palaeobotany and Palynology*, **186**, 5–15.

Blott, S. J., and Pye, K., 2012. Particle size scales and classification of sediment types based on particle size distributions: review and recommended procedures. *Sedimentology*, **59**(7), 2071–2096.

Bluck, B. J., 2011. Structure of gravel beaches and their relationship to tidal range. *Sedimentology*, **58**(4), 994–1006.

Boggs, S., 2001. *Principles of Sedimentology and Stratigraphy*, 3rd edn. Upper Saddle River: Prentice Hall.

Boggs, S., 2006. *Principles of Sedimentology and Stratigraphy*, 4th edn. Upper Saddle River: Prentice Hall.

Byrne, J. V., 1963. Variations in fluvial gravel imbrication. *Journal of Sedimentary Petrology*, **33**(2), 467–469.

Chen, J., Zhang, D. D., Wang, S., Xiao, T., and Huang, R., 2004. Factors controlling tufa deposition in natural waters at waterfall sites. *Sedimentary Geology*, **166**(3–4), 353–366.

Crofts, R. S., 1974. A visual measure of shingle particle form for use in the field. *Journal of Sedimentary Petrology*, **44**(3), 931–934.

Culver, S. J., Bull, P. A., Campbell, S., Shakesby, R. A., and Whalley, B. W., 1983. Environmental discrimination based on quartz grain surface textures: a statistical investigation. *Sedimentology*, **30**(1), 129–136.

Dachnowski, A. P., 1922. The correlation of time units and climatic changes in peat deposits of the United States and Europe. *Proceedings of the National Academy of Sciences*, **8**(7), 225–231.

de Wet, C. B., and Davis, K., 2010. Preservation potential of microorganism morphologies in tufas, sinters, and travertines through geologic time. *Palaeobiodiversity and Palaeoenvironments*, **90**(2), 139–152.

Deotare, B. C., Kajale, M. D., Rajaguru, S. N., Kusumgar, S., Jull, A. J. T., and Donahue, J. D., 2004. Palaeoenvironmental history of Bap-Malar and Kanod Playas of Western Rajasthan, Thar Desert. *Journal of Earth System Science*, **113**(3), 403–425.

Dobkins, J. E., and Folk, R. L., 1970. Shape development on Tahiti-Nui. *Journal of Sedimentary Petrology*, **40**(4), 1167–1203.

Drummond, C. N., Patterson, W. P., and Walker, J. C. G., 1995. Climatic forcing of carbon-oxygen isotopic covariance in temperate-region marl lakes. *Geology*, **23**(11), 1031–1034.

Drysdale, R. N., Taylor, M. P., and Ihlenfeld, C., 2002. Factors controlling the chemical evolution of travertine-depositing rivers of the Barkly karst, northern Australia. *Hydrological Processes*, **16**(15), 2941–2962.

Fairchild, I. J., Smith, C. L., Baker, A., Fuller, L., Sptl, C., Mattey, D., McDermott, F., and Edinburgh Ion Microprobe Facility, 2006. Modification and preservation of environmental signals in speleothems. *Earth Science Reviews*, **75**(1–4), 105–153.

Fernlund, J. M. R., 1998. The effect of particle form on sieve analysis: a test by image analysis. *Engineering Geology*, **50**(1–2), 111–124.

Folk, R. L., 1966. A review of grain-size parameters. *Sedimentology*, **6**(2), 73–93.

Folk, R. L., 1974. *Petrology of Sedimentary Rocks*, 2nd edn. Austin: Hemphill Publishing.

Folk, R. L., and Ward, W. C., 1957. Brazos River bar: a study in the significance of grain size parameters. *Journal of Sedimentary Petrology*, **27**(1), 3–26.

Ford, T. D., and Pedley, H. M., 1996. A review of tufa and travertine deposits of the world. *Earth Science Reviews*, **41**(3–4), 117–175.

Goldberg, P., and Macphail, R. I., 2006. *Practical and Theoretical Geoarchaeology*. Malden: Blackwell Science.

Gutiérrez-Zugasti, I., Andersen, S. H., Araújo, A. C., Dupont, C., Milner, N., and Monge-Soares, A. M., 2011. Shell midden research in Atlantic Europe: state of the art, research problems and perspectives for the future. *Quaternary International*, **239** (1–2), 70–85.

Harrell, J., 1984. A visual comparator for degree of sorting in thin and plane sections. *Journal of Sedimentary Petrology*, **54**(2), 646–650.

Helland, P. E., Huang, P.-H., and Diffendal, R. F., Jr., 1997. SEM analysis of quartz sand grain surface textures indicates alluvial/colluvial origin of the Quaternary “glacial” boulder clays at Huangshan (Yellow Mountain), East-Central China. *Quaternary Research*, **48**(2), 177–186.

Herbert, R. B., Jr., 1995. Precipitation of Fe oxyhydroxides and jarosite from acidic groundwater. *GFF*, **117**(2), 81–85.

Hill, C. A., and Forti, P., 1997. *Cave Minerals of the World*, 2nd edn. Huntsville: National Speleological Society. 463 p.

Kieniewicz, J. M., and Smith, J. R., 2007. Hydrologic and climatic implications of stable isotope and minor element analyses of authigenic calcite silts and gastropod shells from a mid-Pleistocene pluvial lake, Western Desert, Egypt. *Quaternary Research*, **68**(3), 431–444.

Krinsley, D. H., and Doornkamp, J. C., 1973. *Atlas of Quartz Sand Surface Textures*. Cambridge: Cambridge University Press.

Krinsley, D., and Takahashi, T., 1962. Application of electron microscopy to geology. *Transactions of the New York Academy of Sciences*, **25**(1), 3–22.

Krumbein, W. C., 1934. Size frequency distributions of sediments. *Journal of Sedimentary Petrology*, **4**(2), 65–77.

Krumbein, W. C., 1941. Measurement and geological significance of shape and roundness of sedimentary particles. *Journal of Sedimentary Petrology*, **11**(2), 64–72.

Larsen, N. K., and Piotrowski, J. A., 2003. Fabric pattern in a basal till succession and its significance for reconstructing subglacial processes. *Journal of Sedimentary Research*, **73**(5), 725–734.

Lauritzen, S.-E., 2005. Reconstructing Holocene climate records from speleothems. In Mackay, A., Battarbee, R., Birks, J., and Oldfield, F. (eds.), *Global Change in the Holocene*. London: Arnold, pp. 242–263.

Lindsey, D. A., Langer, W. H., and Van Gosen, B. S., 2007. Using pebble lithology and roundness to interpret gravel provenance in piedmont fluvial systems of the Rocky Mountains, USA. *Sedimentary Geology*, **199**(3–4), 223–232.

Lojen, S., Trkov, A., Ščančar, J., Vázquez-Navarro, J. A., and Cukrov, N., 2009. Continuous 60-year stable isotopic and earth-alkali element records in a modern laminated tufa (Jaruga, River Krka, Croatia): implications for climate reconstruction. *Chemical Geology*, **258**(3–4), 242–250.

Long, D. T., Fegan, N. E., McKee, J. D., Lyons, W. B., Hines, M. E., and Macumber, P. G., 1992. Formation of alunite, jarosite and hydrous iron oxides in a hypersaline system: Lake Tyrrell, Victoria, Australia. *Chemical Geology*, **96**(1–2), 183–202.

Marshall, J. R., Bull, P. A., and Morgan, R. M., 2012. Energy regimes for aeolian sand grain surface textures. *Sedimentary Geology*, **253–254**, 17–24.

Middleton, G. V. (ed.), 2003. *Encyclopedia of Sediments and Sedimentary Rocks*. Dordrecht: Kluwer Academic Publishers.

Parkash, B., and Middleton, G. V., 1970. Downcurrent textural changes in Ordovician turbidite graywackes. *Sedimentology*, **14**(3–4), 259–293.

Pentecost, A., 1993. British travertines: a review. *Proceedings of the Geologists' Association*, **104**(1), 23–39.

Pentecost, A., 2005. *Travertine*. Berlin: Springer.

Pettijohn, F. J., 1949. *Sedimentary Rocks*. New York: Harper.

Pizzuto, J. E., Webb, R. H., Griffiths, P. G., Elliott, J. G., and Melis, T. S., 1999. Entrainment and transport of cobbles and boulders from debris fans. In Webb, R. H., Schmidt, J. C., Marzolf, G. R., and Valdez, R. A. (eds.), *The Controlled Flood in Grand Canyon*. Washington, DC: American Geophysical Union. Geophysical Monograph, Vol. 110, pp. 53–70.

Pola, M., Gandin, A., Tuccimei, P., Soligo, M., Deiana, R., Fabbri, P., and Zampieri, D., 2014. A multidisciplinary approach to understanding carbonate deposition under tectonically controlled hydrothermal circulation: a case study from a recent travertine mound in the Euganean hydrothermal system, northern Italy. *Sedimentology*, **61**(1), 172–199.

Powers, M. C., 1953. A new roundness scale for sedimentary particles. *Journal of Sedimentary Petrology*, **23**(2), 117–119.

Renaut, R. W., and Tiercelin, J.-J., 1994. Lake Bogoria, Kenya Rift Valley – a sedimentological overview. In Renaut, R. W., and Last, W. M. (eds.), *Sedimentology and Geochemistry of Modern and Ancient Saline Lakes*. Tulsa: Society for Sedimentary Geology. SEPM Special Publication, Vol. 50, pp. 101–124.

Renaut, R. W., Owen, R. B., Jones, B., Tiercelin, J.-J., Tarits, C., Ego, J. K., and Konhauser, K. O., 2013. Impact of lake-level changes on the formation of thermogene travertine in continental rifts: evidence from Lake Bogoria, Kenya Rift Valley. *Sedimentology*, **60**(2), 428–468.

Renfrew, C., and Bahn, P., 2008. *Archaeology: Theory, Methods and Practice*, 5th edn. London: Thames and Hudson.

Rusnak, G. A., 1957. The orientation of sand grains under conditions of "unidirectional" fluid flow: 1. Theory and experiment. *Journal of Geology*, **65**(4), 384–409.

Russell, R. D., and Taylor, R. E., 1937. Roundness and shape of Mississippi River sands. *Journal of Geology*, **45**(3), 225–267.

Schwertmann, U., Carlson, L., and Murad, E., 1987. Properties of iron oxides in two Finnish lakes in relation to the environment of their formation. *Clays and Clay Minerals*, **35**(4), 297–304.

Smith, J. R., Giegengack, R., Schwarcz, H. P., McDonald, M. M. A., Kleindienst, M. R., Hawkins, A. L., and Churcher, C. S., 2004. A reconstruction of Quaternary pluvial environments and human occupations using stratigraphy and geochronology of fossil-spring tufas, Kharga Oasis, Egypt. *Geoarchaeology*, **19**(5), 407–439.

Smith, J. R., Hawkins, A. L., Asmerom, Y., Polyak, V., and Giegengack, R., 2007. New age constraints on the Middle Stone Age occupations of Kharga Oasis, Western Desert, Egypt. *Journal of Human Evolution*, **52**(6), 690–701.

Sneed, E. D., and Folk, R. L., 1958. Pebbles in the Lower Colorado River, Texas: a study in particle morphogenesis. *Journal of Geology*, **66**(2), 114–150.

Soil Conservation Service, 1975. *Soil Taxonomy: A Basic System of Soil Classification for Making and Interpreting Soil Surveys*. Washington, DC: Soil conservation Service, US Department of Agriculture. USDA/SCS Agricultural Handbook, Vol. 436.

Stein, J. K., and Farrand, W. R. (eds.), 2001. *Sediments in Archaeological Context*. Salt Lake City: University of Utah Press.

Sweeting, M. M., 1972. *Karst Landforms*. London: Macmillan.

Timireva, S. N., and Velichko, A. A., 2006. Depositional environments of the Pleistocene loess-soil series inferred from sand grain morphoscopy – a case study of the East European Plain. *Quaternary International*, **152–153**, 136–145.

Tooth, A. F., and Fairchild, I. J., 2003. Soil and karst aquifer hydrological controls on the geochemical evolution of speleothem-forming drip waters, Crag Cave, southwest Ireland. *Journal of Hydrology*, **273**(1–4), 51–68.

Udden, J. A., 1898. *The Mechanical Composition of Wind Deposits*. Rock Island: Lutheran Augustana Book Concern. Augustana Library Publication, Vol. 1.

US Division of Soil Survey, 1993. *Soil Survey Manual*. Washington, DC: US Department of Agriculture. US Department of Agriculture Handbook, Vol. 18.

Van den Berg, M., Huisman, H., Kars, H., van Haaster, H., and Kool, J., 2010. Assessing *in situ* preservation of archaeological wetland sites by chemical analysis of botanical remains and micromorphology. In Bloemers, T., Kars, H., van der Valk, A., and Wijnen, M. (eds.), *The Cultural Landscape and Heritage Paradox: Protection and Development of the Dutch Archaeological-Historical Landscape and its European Dimension*. Amsterdam: Amsterdam University Press, pp. 161–176.

Wadell, H., 1932. Volume, shape and roundness of rock particles. *Journal of Geology*, **40**(5), 443–451.

Wentworth, C. K., 1919. A laboratory and field study of cobble abrasion. *Journal of Geology*, **27**(7), 507–521.

Wentworth, C. K., 1922. A scale of grade and class terms for clastic sediments. *Journal of Geology*, **30**(5), 377–392.

Wilson, M. J., 2004. Weathering of the primary rock-forming minerals: processes, products and rates. *Clay Minerals*, **39**(3), 233–266.

Wolfe, M. J., 1967. An electron microscope study of the surface texture of sand grains from a basal conglomerate. *Sedimentology*, **8**(3), 239–247.

Yu, X., Zhou, W., Liu, X., Xian, F., Liu, Z., Zheng, Y., and An, Z., 2010. Peat records of human impacts on the atmosphere in northwest China during the late Neolithic and Bronze Ages. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **286** (1–2), 17–22.

Zhang, D. D., Zhang, Y., Zhu, A., and Cheng, X., 2001. Physical mechanisms of river waterfall tufa (travertine) formation. *Journal of Sedimentary Research, Section A: Sedimentary Petrology and Processes*, **71**(1), 205–216.

Zheng, G., Lang, Y., Miyahara, M., Nozaki, T., and Haruaki, T., 2007. Iron oxide precipitate in seepage of groundwater from a landslide slip zone. *Environmental Geology*, **51**(8), 1455–1464.

Zingg, T., 1935. Beitrag zur Schotteranalyse: Die Schotteranalyse und ihre Anwendung auf die Glattalschotter. *Schweizerische Mineralogische und Petrografische Mitteilungen*, **15**, 39–140.

Cross-references

Alluvial Settings
Archaeological Stratigraphy
Cave Settings
Chronostratigraphy
Coastal Settings
Colluvial Settings
Dumps and Landfill
Eolian Settings: Loess
Eolian Settings: Sand
Glacial Settings
Grain Size Analysis
Mass Movement
Microstratigraphy
Paleoenvironmental Reconstruction
Paludal Settings (Wetland Archaeology)
Radiocarbon Dating
Rockshelter Settings
Shell Middens
Site Formation Processes
Soils
Speleothems
Spring Settings
Stable Carbon Isotopes in Soils
U-series Dating
Volcanoes and People

SHELL MIDDENS

Katherine Szabó
Centre for Archaeological Science, School of Earth and Environmental Sciences, University of Wollongong, Wollongong, NSW, Australia

Synonyms

Conchero (Spain); Escargotières (land snail middens); Kitchen midden; Køkkenmødding (Denmark); Sambaqui (Brazil)

Definition

A refuse deposit in which molluscan shell is one of the major constituent materials.

Identifying shell middens

Shell middens are refuse deposits composed solely or primarily of molluscan shells. Although they are most frequently thought of as comprising the refuse of ancient human meals, shell waste piles can also be accumulated through other cultural behaviors such as building and industrial activities. The recognition of shell middens in the landscape is not always a simple matter. Some nonhuman animals (e.g., crabs, octopuses, and muskrats) create shell middens. Additionally, a range of natural coastal and landscape processes can generate piles of molluscan shell prompting debates as to their origin. Thus, from a geoarchaeological perspective, the task of differentiating cultural middens from natural geomorphologic shell-bearing features and nonhuman animal middens is fundamental.

There is no simple checklist that allows archaeologists to distinguish naturally and culturally accumulated shell deposits, and frequently, shell-bearing deposits are formed and then transformed by *both* natural and cultural agents. Nevertheless, through consideration of stratigraphy and evidence for formation processes, constituent elements, and taphonomic signatures, a robust case as to origin can be built.

Location

Shell middens tend to be accumulated close to the aquatic area from which the mollusks derive, whether in a coastal, lacustrine, or riparian location (Peacock, 2000). Such middens may represent, among other things, processing points where bulky and heavy shells were discarded to facilitate easier transport of the meat, mealtime camps used while moving from one place to another, seasonal occupation areas, or zones within a larger habitation area or site complex. The locations of middens today may be broadly indicative of the locations of coastlines and watercourses in the past (e.g., Cannon, 2000). The global rise of sea levels at the end of the Pleistocene surely drowned innumerable coastal midden deposits (Bailey and Flemming, 2008).

Middens may also indicate the nature of past aquatic environments and thus provide valuable evidence for long-term ecological modeling (e.g., Graham et al., 2003). Considerable potential exists for developing research relationships with coastal and earth scientists by introducing shell midden data into integrated ecological models. Shell middens are not accreted through standard littoral processes, and they often lie beyond the reach of many natural taphonomic processes of the coastal zone (e.g., wave action and its associated actions of sorting, fragmentation, and attrition). As such, they present an entirely different category of evidence that is frequently well dated and well preserved. In a freshwater context, Peacock (2000, 193) adroitly sums up this potential: “[l]

arge archaeological shell assemblages can, in general, be considered qualitative collections that provide a good representation of past aquatic environments and how these environments changed through time."

Natural geomorphic accumulations vs. cultural middens

Natural geomorphic accumulations of shell often form in places similar to those where shell middens are accumulated by humans. Given this similarity, debate and methodological attention have been devoted over the past decades to distinguish the signatures of these two broad types of shell deposit. Attempts have been made to outline criteria that would assist in separating natural and cultural shell accumulations (e.g., Attenbrow, 1991; Henderson et al., 2002; Rosendahl et al., 2007); however, all authors rightly point out that assessment is always context driven, and there is no universally applicable checklist. Despite these limitations, the following key attributes and useful lines of inquiry can help guide assessment.

The most common and widespread type of large natural shell accumulation is the *chenier*. Cheniers are a form of stranded beach ridge that is often composed of poorly sorted shells. They can be accreted through a variety of coastal processes, but usually through longshore drift depositing coarse material over a finer substrate or through wave action winnowing out finer sediment on a prograding shoreline (Augustinus, 1989; Woodroffe and Grime, 1999). Their position, shell-rich nature, and the fact that major constituent taxa are frequently the same mean there can be confusion differentiating these from anthropogenic shell middens (Henderson et al., 2002). The inclusions of artifacts, other faunal remains, and charcoal are clear indicators of human agency (Figure 1); however, midden deflation and reworking, as well as dedicated processing sites which may have little in the way of unequivocal archaeological material (see the northern Australian case below), may complicate recognition.

Cheniers and chenier plains have been extensively studied within the field of coastal geomorphology, and both the general approach to analysis employed and the specific criteria developed to identify chenier-building processes can assist archaeologists in the assessment of ambiguous shell-rich deposits. The geomorphological approach to shell deposit analysis developed by Kidwell et al. (1986; see also Kidwell and Holland, 1991) offers a useful framework for field description that further assists interpretation: the lateral extent, geometry, thickness, dip, and nature of contacts are all considered along with observations on taxonomic composition, bedding, and the orientation of shells relative to each other and other facies. An initial geomorphological assessment of shell-bearing deposits not only helps to determine whether the shell assemblage has been accreted through natural processes, but it also helps in pinpointing potential disturbances of shell middens by factors such as later wave action or deflation through aeolian action (e.g., Rick, 2002). Moreover,

Shell Middens, Figure 1 Surface bone, lithic artifacts, charcoal, and midden shell indicating the presence of a shell-bearing archaeological site, northwestern Australia (Photograph by Brent Koppel).

the structured language provided by geomorphology allows communication between fields of inquiry and provides a clear set of descriptors for archaeological reporting.

Taphonomic signatures

Geomorphological methods are most useful in characterizing shell accumulations; however, distinctive patterns of individual shell breakage and taphonomic alteration can also provide practical clues to processes involved in the formation and transformation of the deposit. Many archaeologists, notably specialist archaeomalacologists (archaeologists who specialize in the study of archaeological shell), routinely assess samples for evidence of bioerosion, natural aquatic encrustations, and natural attrition such as beach-rolling and sand-blasting (see Claassen, 1998, 54–70). Much of this knowledge has been adapted from the natural sciences, where the literature on taphonomic processes and molluscan shell is more extensive (e.g., Vermeij, 1995; Zuschin et al., 2003). The study of bioerosion and the recognition of various trace fossils (ichnos) comprise a well-developed field of study within (1) marine biology and paleontology (e.g., see Chazottes et al., 1995; Kowalewski and Labarbera, 2004) and (2) the ecology and diagnostic traces of taphonomic agents such as boring sponges (*Cliona* spp.) and fungi, encrusting algae, and a wide variety of worms (especially polychaetes and sipunculids). Detection of the distinctive traces of these creatures can provide important proxy information on the nature of inshore habitats, as well as whether the shell was introduced to the site live or dead.

Although shell accumulations with extensive evidence of the action of natural taphonomic agents may indicate that the deposit is of natural rather than cultural origin, there are some circumstances where natural shell may be introduced – sometimes in considerable quantities – to archaeological sites. Empty shells may be collected as raw materials for artifact production, and on a much larger scale, considerable amounts of natural shell may be introduced into archaeological sites as construction material (e.g., see Ronen, 1980).

Species and size-class representation within a shell accumulation has also been used to argue for or against an archaeological origin. It is generally assumed, and often true (e.g., Anderson, 1981), that gatherers will focus their collecting upon particular molluscan taxa and/or shells of larger sizes. Following from this, middens tend to be a selective subset of the species and size classes found in local habitats. Although this is a useful rule of thumb, human practices such as fine-grained gathering strategies and mass harvesting, or differential survivorship in natural shell accumulations due to taphonomic factors, will produce assemblages that diverge from this norm.

Animal agents of midden formation and transformation

Some animals capture and consume mollusks as part of their diet and in the process create localized middens. Such species include octopuses (Ambrose, 1983), mud crabs (Silliman et al., 2004), muskrats (Hanson et al., 1989), and birds (Jones and Allen, 1978; Erlandson et al., 2007). While there has been little dedicated study on the predation patterns and signatures of such fauna within archaeology, research within various natural science disciplines has outlined distinctive breakage patterns and characteristics (e.g., see Vermeij, 1995, for a variety of taxa, but especially crabs; Nixon et al., 1980, for octopus drilling). These signatures, coupled with the location, species composition, and additional constituent elements of the midden, can indicate a nonhuman agent of accumulation.

One of the more high-profile debates surrounding the natural or cultural origins of concentrated shell deposits concerned the Weipa shell mounds of northeastern Australia. This complex of around 500 shell mounds situated around the convergence of four river mouths in Albatross Bay, Cape York, comprises small deposits less than 5 m in diameter and 0.5 m thick to step-sided mounds reaching 13 m in height (Bailey et al., 1994). An intensive study by Bailey in the 1970s (Bailey, 1977) specifically addressed suggestions that the shell mounds were of natural origin (e.g., Stanner, 1961). Through comparison of natural shell bank and hypothesized midden deposits, Bailey (1977) argued that the midden material showed deliberate selection of both species and size classes of mollusk as well as yielding animal bone, charcoal, and bone and stone tools. He further argued, following Peterson (1973), that the larger mounds provided a wet-season refuge above the floodplains, thus promoting ongoing use and deposition (Bailey, 1977).

Bailey's cultural interpretation of the Weipa middens was insistently challenged by Stone (1989), who argued that the sites were the product of the mound-building scrub-fowl megapode. These birds (*Megapodius reinwardt*) build nest mounds alongside waterways and estuaries, and the nest mounds can remain in use for sufficient time to attain sizes of up to 5–10 m in height (Stone, 1989). The birds will rake up any surrounding material with their feet, including extant shell middens (Stone, 1989). The ensuing debate involved further test excavations, radiocarbon sequences, and geomorphological research, as well as considerable dissection of both data and interpretations (Bailey, 1991; Stone, 1991, 1995; Bailey et al., 1994).

Although never resolved to Stone's satisfaction, the debate served to draw out many of the finer points regarding how a midden is constituted and what is sufficient evidence to argue that a shell deposit is a midden-mound. Taken individually, features such as size selection in shells can be interpreted as wave sorting and ash lenses as the result of bushfires rather than campfires. A paucity of stone tools can point to the scarcity of raw materials on the landscape or the absence of cultural input into a deposit. However, the strength of Bailey's argument was in drawing together the different lines of evidence, from positioning on the landscape to radiocarbon sequences showing incremental deposition through time to the various constituent materials and their taphonomic condition (Bailey, 1977, 1991; Bailey et al., 1994).

Another permutation of the natural/cultural debate surrounding shell deposits involves the transformation of cultural middens by nonhuman agents. In these cases, there are likely to be items of material culture and other clear indicators of human cultural input. Bioturbation on different scales, from insect activity to crab burrowing (Specht, 1985) to rodent burrowing (Bocek, 1986), and earthworm activity (Stein, 1983), as well as trampling (Gifford-Gonzales et al., 1985), can mix deposits and introduce noncultural material into a cultural shell midden. Cultural material can also be removed or destroyed through the actions of scavengers or birds such as bowerbirds of Australia and New Guinea, the males of which are known to take shell midden material for display in their "bower" designed to attract a mate (Dwyer et al., 1985) (Figure 2). Terrestrial hermit crabs (Coenobitidae), which are common across the tropics, are not only scavengers but also remove gastropod shells from cultural middens and replace it with their old shell of unknown original age and provenance (Szabó, 2012).

Midden formation and taphonomy

A variety of taphonomic signatures exist that can help researchers distinguish between natural and cultural shell accumulations, yet there is a further layer of analytical questioning that can provide insights into the formation and taphonomic processes of definite midden deposits. These analytical directions can inform on such diverse things as aspects of past human mobility, settlement patterns and logistical landscape use, the processing and

Shell Middens, Figure 2 Bowerbird (Ptilonorhynchidae) bower with shells taken from a nearby prehistoric midden forming the "court" (Photograph by Yinika Perston).

Shell Middens, Figure 3 A modern midden built up by intensive seasonal shell gatherers and processers of the Saloum Delta, Senegal (Photograph by Katherine Szabó).

consumption of food, and establishing the different uses of shell on the spectrum from the everyday prosaic to ritual deposits.

Deposition patterns and signatures

An enduring discussion of the broad types of shell accumulations in the archaeological record was presented by Widmer (1989) as a conference paper in the context of Florida archaeology, and it has been reiterated and discussed, and sometimes adopted, in a number of published works (e.g., Claassen, 1991; Rabett et al., 2011). He defines four key types of shell-bearing site (as summarized in Claassen, 1991, 252):

1. Shell midden site – secondarily deposited shell from food consumption with no other activities evident at the site.
2. Shell midden – discrete lens or deposit of shell only.
3. Shell-bearing midden site – a site composed of secondary refuse of many kinds, including shell, generated by a wide range of activities.
4. Shell-bearing habitation site – primarily shell debris in the site matrix used for architectural needs; the shell may or may not have originated as food debris.

Such attempts at classification to untangle the nature and formation of different types of cultural shell accumulation are useful heuristics, particularly at the local level. However, when applied more broadly than their intended descriptive context, the divisions are often uncomfortably narrow or all-inclusive. Aside from potential culturally specific "types" being omitted or undifferentiated within the general schema, the type boundaries themselves may be open to question for different regions and time periods. This is especially so when particular "types" are linked as a matter of course to particular behaviors or sectors of society. As Claassen (1991, 252) explains, sites with quantities of shell and few artifacts are often interpreted as women's dinnertime or food processing camps – an interpretation that may or may not be fair depending on the site, time period, and social group under discussion.

Regardless of time period or area of the world, investigation of a number of significant criteria can help to determine how a shell midden accumulated and what information the shell midden site may contain about aspects of past cultures.

Ethnoarchaeological studies into aspects of shell midden site formation, such as those presented in Godino et al. (2011), contribute to refining interpretations and enhancing methodological approaches to excavation, sampling, and analysis. Godino et al. applied multiple analytical techniques, including micromorphology, phytolith, and lithic analyses, to ethnographically documented deposits, allowing process and interpretation to be linked with a high degree of certainty. A multistranded analytical approach informed by ethnographic observation was also used by Ham (1982) in his study of Coast Salish shell middens of northwestern North America.

A central concern of these and other similar studies is to investigate the variety of activities that contributed to the building of shell midden deposits and the length of time over which this took place. This concern is often coupled with the recognition that shellfish-gathering behavior recorded ethnographically is often a seasonal undertaking (Figure 3). Investigations of seasonality through the analysis of seasonal banding and stable isotope analysis are discussed below, and other techniques are frequently used to establish the periodicity of site occupation as well. Stein et al. (2003) utilized fine-grained radiocarbon dating to obtain a better understanding of the accumulation rates and patterns in the San Juan Islands, Washington State, United States. In contrast, Parkington (2012) used the differences noted between various site types in the Elands Bay and Lamberts Bay regions of South Africa to argue that coastal "megamiddens" are not residential sites but the remains of intensive, seasonal mussel-gathering, and preservation practices (but see Jerardino, 2012, for an alternative interpretation).

Reworking patterns and signatures

Shell middens may be built up incrementally in either a gradual or more punctuated fashion, slowly or rapidly, but regardless of the original mode and temporality of deposition, there is always a range of processes which can rework shell midden deposits and complicate chronostratigraphic patterning. Bioturbation issues have been discussed above, and plants are also a well-recognized agent of disturbance, but many non-biological processes can also substantially transform shell midden deposits. Most notably, transformational processes are geomorphic, or they stem from the elemental processes of wind and water.

Shell middens in the open, as opposed to protected cave or rockshelter locations, are regularly exposed to the elements. Water will be dealt with in the next section. Wind can have a major effect on shell midden deposits – a fact that has been underplayed in much of the literature. The removal of fine material and matrix sediments by wind leads to deflation, which biases the sequence through attrition. A study of the impact of aeolian processes (Rick, 2002, see also Wandsnider, 1988) revealed that there was major displacement of lighter archaeological elements such as fishbone, leaving relatively denser concentrations of the heavier elements such as mammal bone and shell. Windblown sand can also leave visible traces such as etching, abrasion, and polishing of bone and shell surfaces, affecting deposits to a depth of around 20 cm (Rick, 2002).

Koike's classic study (Koike, 1979) explored, among other things, the degree of displacement of individual shells within a midden deposit. She refitted 380 *Meretrix lusoria* valve pairs from a total of 2,089 unbroken valves from the Natsumidai site near Tokyo Bay, Japan. From the Natsumidai molluscan valve-pairing data, she estimated that less than 70 % of the shell midden material was preserved and that most valves were separated by five or more centimeters from their partner valve. Vertical movement was found to be less than horizontal movement (Koike, 1979).

Humans themselves can also significantly transform deposits through a wide range of actions, including the construction of fires and trampling. Micromorphological analysis of midden sediments has considerably enhanced our ability to detect episodes of burning within a stratigraphic midden sequence (e.g., Shillito and Matthews, 2013), and shell is easily detected within thin sections (Shillito et al., 2011). The effects of trampling on the fragmentation and displacement of shell within middens have received some investigation, but more work on this important process is undoubtedly required. Experimental work on trampling was undertaken by Muckle (1985), who considered fragmentation and vertical displacement using three bivalve species (*Saxidomus gigantea*, *Leukoma* (=*Protothaca*) *staminea*, and *Mytilus edulis*). Unsurprisingly, the more fragile mussel shell, *Mytilus edulis*, was the most heavily fragmented, but downward displacement for all three species was negligible (Muckle, 1985).

Preservation patterns and signatures

There is a close relationship between fragmentation and preservation in midden shell: the less well preserved a shell, the more liable it is to fragment, and the more fragmented a shell, the less resilient it is to taphonomic processes. There are several key factors that can affect preservation within a shell midden, including pH, the percolation and penetration of water, and the dynamics between constituent materials.

Being constructed of calcium carbonate ($CaCO_3$), molluscan shells preserve best in alkaline environments, and by virtue of their mass within a shell midden, they can create an alkaline matrix themselves. This favors the preservation of constituent materials, such as bone, but it is not conducive to the preservation of plant microfossils, such as phytoliths (Piperno, 1985). Conversely, shell and shell middens will not preserve well in acidic sediments, and the release of tannins and acids by plants and decaying plant matter will quickly eat away at shell. In the acidic swampy deposits of the subantarctic Auckland Islands, the calcareous parts of mussels from shell midden deposits were nearly entirely dissolved, leaving only numerous paperlike fragments of the organic outer periostracum of the shells (Anderson, 2005).

The brittleness and size of mollusk shells means that shell middens are often quite porous, allowing for the easy percolation of water. Rainwater is slightly acidic, and thus shell middens exposed to rain will be more prone to dissolution than those in sheltered locales. The process, as explained by Claassen (1998, 60), involves the combination of rain and atmospheric carbon dioxide to form a weak carbonic acid. This carbonic acid reacts with the calcium carbonate of the shell to form water-soluble calcium bicarbonate, thus resulting in dissolution. Groundwater and other freshwater that is undersaturated in calcium will dissolve shell more rapidly than that which is oversaturated (Claassen, 1998, 59). Archaeochemical analyses of elemental concentrations in sediments can also sometimes detect the presence of relict shell middens or those that have visibly disappeared (e.g., Beck, 2007).

Since shell fragmentation is both a result of, and a contributor to, the action of taphonomic processes, analyses focused on fragmentation can provide insights into many aspects of site formation and transformation. One strand of analysis treats shell middens within a geomorphological framework; it sees shell fragments as "bioclasts" that can inform about deposit formation and transformation processes (Stein, 1992). Thus, sedimentological approaches such as grain size analysis can be applied to archaeological shell midden fragments to assess stratigraphic variations in fragment size in order to make inferences about their biological and sedimentological sources (Ford, 1992). Differential fragmentation of midden shell can interfere with the accurate quantification of samples (see Gutiérrez Zugasti, 2011), and it can complicate the construction of metrical profiles for species within a midden (Jerardino and Navarro, 2008; Faulkner, 2010).

Types of shell midden

Morphology and classification

Although shell middens can be broadly construed as shell refuse deposits, variations in density and depositional patterns can produce a number of classifiable, mostly locally specific morphologies – see Claassen (1991) and the discussion above. Among the better known examples are shell rings and shell mounds. Shell rings are most readily associated with the Southeastern United States, being found along the coastlines of Florida, Georgia, and South Carolina. These rings, sometimes fully closed circles and sometimes horseshoe in shape, were deliberately constructed architectural features up to 250 m in length and 6 m high (Saunders and Russo, 2011). Constructed from ca. 4,800 cal BP, radiocarbon dating and geoarchaeological analysis has established that largely unfragmented shell was rapidly amassed to form the ring structure. Whether these distinctive shell midden deposits were refuse heaps associated with residential structures, water traps, or ceremonial spaces of some type is still debated (Trinkley, 1985; Marquardt, 2010; Saunders and Russo, 2011). In Jomon period, Japan, large horseshoe-shaped middens suggest long-term use rather than intensification of resource exploitation (Habu et al., 2011). Smaller-scale shell rings recorded in Tierra del Fuego, Argentina, have been shown through the use of various geoarchaeological techniques, including microfacies analysis (Villagran et al., 2011a; see also Verdún, 2010), to be midden deposits accreted around the perimeter of individual huts.

Shell mounds are found worldwide, although they tend to be concentrated in particular geographic locations due to a variety of factors, such as proximity to extensive shellfish beds, forager logistics and mobility patterns, and favorable conditions for preservation. Three of the best-known archaeological shell mound locales are northern Australia, the United States, and Brazil. Aspects of the northern Australian shell mounds have been discussed above, and steady archaeological work continues to elucidate why shell mounds accrete at particular periods in northern Australian prehistory (e.g., Morrison, 2013) (Figure 4).

In Brazil, *sambaqui* is the term given to large shell mounds – 10–50 m in height and 50–500 m long – located along the coastline of the southeastern states

Shell Middens, Figure 4 Excavation in progress at Garangarri BMB/029, an *Anadara granosa*-dominated shell mound on the northern margin of the Durabudboi River wetland system, Point Blane Peninsula, northeast Arnhem Land, Australia (Photograph courtesy of Patrick Faulkner).

(Villagran et al., 2011b; Wagner et al., 2011). While much of the constituent material of well-studied *sambaqui* can be categorized as "midden" in that it consists of burnt shell, fish bones, and charcoal, archaeofacies analysis suggests that this would be too simplistic an interpretation (Villagran et al., 2009). Human burials are common within *sambaqui*, and detailed studies of the sediments suggest that much of the midden material has been translocated from an original processing site elsewhere and that other faunal remains may be related to feasting associated with mortuary rituals (Villagran et al., 2009). Thus, *sambaqui* shell middens perhaps represent, simultaneously, deliberately redeposited matrix and the remnants of significant cultural rituals. The "Shell Mound Archaic" sites of the south-central United States also present a complex picture of construction and use, with human interments common and the frequency of still-articulated bivalves suggesting a lack of trampling and movement that one would expect to see in a midden associated with a habitation site (Claassen, 1998).

Despite the size of many of these mound deposits globally, detailed study has made it clear that many are not composed of in situ shell midden per se. In many of these cases, such as those outlined above, shell mounds had a social function closely tied to ritual rather than simply evidencing the ordered disposal of waste. Where large mounds are argued to be subsistence detritus, there is frequently debate over the extent to which the mollusks actually contributed to overall diet (e.g., Bailey, 1975; Meehan, 1977, 1982; Erlandson, 1988). The answer, from a simple calorie-based perspective, is generally argued to be not very much (Bailey, 1975). The durability of shells and their large size relative to the meat package they contain are the reasons often provided for the extensiveness of shell midden deposits by analysts (e.g., Bailey, 1975). Nevertheless, ethnographic studies of shellfish gathering demonstrate that mollusks are a reliable food source that can be easily collected by virtually all members of the community, from the very young to the very old (e.g., Meehan, 1982). As such, the niche they fill in subsistence structures in social terms can be very important.

Large shell mounds can also give the impression that the course of their accumulation encompassed a considerable span of time. Although this is sometimes the case, detailed studies in Washington State, United States, have demonstrated that middens can accumulate rapidly (Stein et al., 2003). The commentary of Stein et al. concerning the calculation and interpretation of accumulation rates offers valuable pointers to anyone excavating or studying concentrated shell mounds.

Shell mounds in a number of locations around the world are considered to be at risk, as they are often mined for shell for modern construction and fill (Ceci, 1984). Such is the case with some *sambaqui* (Villagran et al., 2009; Wagner et al., 2011) and some of the deposits considered by Henderson et al. (2002), as well as many more.

Although discussion of large shell mounds has enjoyed a place of prominence within the global literature, shell midden deposits come in a wide variety of shapes and forms. Strictly defined as refuse deposits dominated by molluscan shell, scatters, lenses, and smaller concentrations are common and widespread. While some of these forms bear a close resemblance to their original state of deposition, taphonomic processes (such as midden deflation due to aeolian reworking) can substantially transform the visible appearance, and sometimes internal constituents, of shell midden deposits (e.g., Rick, 2002). Clearly, detection of postdepositional reworking is critical, as small or diffuse shell middens can provide clues about logistical mobility, resource catchments, and use by past peoples.

Non-coastal settings: freshwater and terrestrial shell accumulations

Coastal middens comprising marine and/or estuarine shell are common globally, and discussions of marine shell middens tend to dominate the literature. However, shell middens or shell mounds containing largely freshwater molluscan or land snail remains are important archaeological deposits in particular places and time periods. Some extensive freshwater mussel shell mounds of the Southeastern United States have been discussed above, with freshwater mussel middens related to the historic button-manufacture industry discussed below.

Where freshwater shell deposits contain clear archaeological indicators such as artifacts, burials, and features, there can be little doubt as to their anthropic origins. However, for freshwater shell accumulations lacking such unequivocal archaeological features, demonstrating that they are anthropogenic deposits can be altogether more challenging. In such cases, a geoarchaeological approach is vital. Such was the case with the recently investigated Early and Mid-Holocene "forest islands" of the seasonally inundated savannahs of lowland Bolivia (Lombardo et al., 2013). Hundreds of enigmatic vegetated mounds raised above the grasslands of the Llanos de Moxos had previously been interpreted as bird rookeries and/or relict landforms (Hanagarth, 1993; Langstroth Plotkin, 1996). Coring of several forest islands, and excavations at one, revealed a Holocene sequence dominated by freshwater gastropod remains together with lesser amounts of bones from diverse types of vertebrate fauna (Lombardo et al., 2013). The complete absence of stone tools or other distinctive items of human presence in pre-pottery levels meant that a potential case for human accumulation rested on the chemistry of the sediments, the patterns of shell accumulation and discard, and observed geomorphic patterns in the context of the wider landscape. Archaeochemical analyses indicated elevated concentrations of black carbon, phosphorus, and coprostanol (a biomarker for the presence of human fecal material) in the mound sediments, thereby demonstrating anthropic input. Furthermore, concentrations of black carbon and C_{org} in the mound were 20–30 times higher than in the abutting, contemporaneous paleosol, confirming regular, localized burning on the mound surface (Lombardo et al., 2013).

While freshwater mollusks have been a heavily exploited resource, their remains producing large shell middens in many parts of the world, the role of land snails (gastropods) in past subsistence regimes, and the existence of midden sites associated with land snail consumption are rarer. Land snails are commonly encountered in low frequencies within marine or freshwater middens, especially in well-vegetated settings. Often, they are self-introduced into deposits, with scavenging snails being attracted to fresh refuse deposits and herbivorous land snails drawn toward the rich source of $CaCO_3$ for shell building that a shell midden offers (Evans, 1972). Some analysts have noticed that land snail accumulations are concentrated in sterile layers (Miracle, 1995), thus indicating natural occurrence and also providing a useful stratigraphic marker in complex deposits (Szabó, 2015). Having small home ranges, land snails can be valuable proxies for the nature of the environment and vegetation immediately around the site at particular points in time (Evans, 1972). The presence of stowaway invasive land snails can also provide insights into the movement of people and plants (e.g., Christensen and Kirch, 1981).

In contrast to self-introduced assemblages, land snails were intensively gathered in some parts of the world as an important subsistence resource, as evidenced by large midden mounds. The most well-known land snail middens are the *escargotières* of the Maghreb (Algeria, Morocco, and Tunisia) and Libya (Cyrenaica) (Lubell et al., 1976), of which there are thousands, ranging in size from a few to several hundred meters in spatial extent, and from 1 to 3 m in thickness (Lubell, 2004). Many more land snail concentrations from sites around the Mediterranean and Near East are variously interpreted as either middens or natural death assemblages (see Lubell, 2004, for discussion; Taylor et al., 2011), although a survey of the literature shows that there are no clear and systematically applied criteria for separating one from the other.

Land snail assemblages that are very selective and exclude small or micro-taxa suggest deliberate collection, although modern samples and ecological information should underpin any judgments in this regard. The large Hoabinhian land snail middens of Vietnam (e.g., Rabett et al., 2011) are dominated by one or two large snail species and do not reflect the diversity of species to be found in immediately adjacent environments. The selective presence in hearths of large *Ryssota* sp. land snails in the Batanes Islands of the northern Philippines, coupled with contemporary local traditions of land snail collection and consumption, also presents a strong argument for past exploitation (Szabó et al., 2003). Intra-site and stratigraphic patterning can also provide useful information, such as in the case of sterile layer accumulations noted above as well as the clustering of land snail remains closer to cave mouths rather than further into a cave (e.g., Medway, 1960, 376; Szabó, 2015).

Nonfood refuse middens

Although shell middens are generally composed of discarded food remains, they can represent the cultural waste of other processes in some situations. Such deposits include piles of shell waste from the extraction of bait for fishing (Claassen, 1998, 176–178), preparation areas for the production of lime used in construction and industry (e.g., Panda and Misra, 2007), and shell middens related to the industrial or specialized production of shell artifacts, among others. Cultural accumulations of shell, either from natural deposits or secondarily used midden shell, have also been recorded archaeologically as constructed living surfaces (e.g., Onat, 1985) or deliberate inclusions in agricultural soils (e.g., Barber, 2013). Valuable insights into the cultural accumulation of shell middens not related to food procurement can often be found in relevant historical and ethnographic literature.

One of the most comprehensively reported types of nonfood refuse shell midden is broken shells of particular species within the Muricidae used in the production of colorfast purple dye for textiles (Reese, 1980). Evidence for the production of "Tyrian purple" or "royal purple" and "biblical blue" muricid dyes stretches back around four millennia, with production centers around the Mediterranean basin and Levant through to the Arabian Peninsula (Edens, 1999; Reese, 2010). Text-based resources do not give a full account of the dyeing process, so archaeological and experimental work (e.g., Koren, 2005; Ruscillo, 2005) have been brought together to give an accounting of both the history and process of muricid dye production.

Several species of mollusk within the Muricidae were collected and processed for dye production, including *Hexaplex* (=*Murex*) *trunculus*, *Bolinus* (=*Murex*) *brandaris*, and *Stramonita* (=*Thais*) *haemastoma*, with each species being processed in a different way and yielding a different shade of dye (Ruscillo, 2005). In the Arabian Gulf, the local species *Thalessa* (=*Thais*) *savignyi* was used (Edens, 1999), and there is evidence for the use of the muricid species *Nucella lapillus* and *Ocenebra erinaceus* in dye production in France and elsewhere in Atlantic Europe (Dupont, 2011). A tiny amount of the fluid that generates the dye can be found within the hypobranchial gland of each animal, and thus large quantities of individuals are needed for commercial dye production as evidenced by replicative studies (e.g., Koren, 2005; Ruscillo, 2005). In order to extract the gland, the shell needed to be either pierced or fragmented to expose the salient portions of the animal, and thus large deposits of these shells broken in such ways constitute one line of evidence for purple-dye production.

It is likely that shells were generally collected by hand or by using a baited trap (Ruscillo, 2005; Çakırlar and Becks, 2009); however, biostratinomic evidence from purple-dye middens indicates that occasionally murex shells could have been "farmed." Spanier (1986) described the presence of predatory boreholes in *H. trunculus* made by other individuals of the same species. Through experimental studies, he established that conspecific cannibalism was likely to happen only under artificial conditions, and he suggested that some ancient dyers could have kept quantities of *H. trunculus* alive in containers of seawater for several weeks.

Although large quantities of broken murex shells associated with dyeing paraphernalia or remnants of the pigments themselves provide strong evidence for murex dye production, smaller, inland, or otherwise ambiguous murex deposits have been the subject of much debate. As summarized by Çakırlar (2009,128–129, also Çakırlar and Becks, 2009), murex species used in dye production are also edible and have recorded uses as bait for fishing, as building materials, and in burnt form as lime or pottery temper. Carannante (2011) considers a number of ambiguous murex deposits and suggests that quantities of crushed shell from dye production could have been transported to other locales for transformation into lime or pottery temper. The movement of shell artifact production waste for secondary use is also recorded for Tikal, Guatemala (Moholy-Nagy, 1997). Given the variety of known uses for murex snails in the Eastern Mediterranean, contextual evidence from excavations and careful taphonomic evaluations are critical to robust interpretations of fragmented murex shell deposits.

Industrial waste from the intensive production of shell artifacts can also produce distinctive non-subsistence-related midden deposits. Claassen (2010) provides an instructive example focused upon the historic freshwater mussel-shell button industry of the United States, where tens of thousands of tons of shells were harvested from rivers such as the Mississippi and Illinois. Primary processing of the shells usually happened near the capture site, with the cutting of buttons taking place either in the

Shell Middens, Figure 5 Waste *Pinctada* sp. pearl oyster shell from mother-of-pearl button manufacture (Photograph by Katherine Szabó).

same locale or after transport to a dedicated facility. Claassen (2010, 308) draws attention to the amount of waste produced by this industry in terms of failed blanks and waste shell after cutting (Figure 5). Large piles of shell could also be stockpiled by riverbanks in the hope of a later sale (Claassen, 2010, 305).

Industrial workshops, albeit on a smaller scale, have been identified archaeologically around the world. The presence of broken blanks and preforms, waste shell raw materials, and manufacturing tools underpins the identification of such shell midden deposits. The manufacture of sacred chank shell (*Turbinella pyrum*) objects, predominantly bangles, in Harappan and early historic Indian centers is attested through the presence of quantities of debitage, and some production sites have been identified (Deshpande-Mukherjee, 2008). Intensive, localized shell bead production also leaves significant quantities of shell and lithic waste (e.g., Nigra and Arnold, 2013, for the Chumash, USA; Yerkes, 1989a; Yerkes, 1989b, for Mississippian sites, USA; Allen et al., 1997, for Papua New Guinea).

A number of Caribbean sites show evidence for the systemic production of adzes from the lip of the large queen conch (*Strombus gigas*) shell (Keegan, 1984; Serrand and Bonnissent, 2005). However, as with the muricid shells associated with dye production, *S. gigas* was a valued food source as well. Extensive deposits of shells systematically broken to extract the meat are associated with the intensive harvesting and preservation of *S. gigas* flesh for later transport and consumption (Antczak et al., 2008). The scale of this operation was immense, with over 4.5 million *S. gigas* shells recorded at single locality in the Los Roques Archipelago, Venezuela. Modeling of the nature and ecological impact of such high levels of exploitation have immediate relevance to contemporary resource management issues (Cipriani and Antczak, 2008).

It has been suggested that shell midden deposits in other parts of the world were associated with mass processing and preservation of mollusks, and a significant ethnographic record also exists. The increased number of shell midden deposits in the late prehistory of New England has been interpreted as an intensification of shellfish collecting and preservation by women as part of burgeoning trading activities (Williams and Bendremer, 1997). "Megamiddens" along the Southwest Cape of South Africa contain many thousands of m^3 of fragmented black mussels (*Choromytilus meridionalis*). Megamidden formation has been associated with intensive mussel collecting and drying activities (Henshilwood et al., 1994; Jerardino, 2012).

Fundamental analytical techniques

Identification

Correct taxonomic identification is central to a good midden analysis as well as effective sampling strategies for the application of scientific techniques, such as radiocarbon dating or stable isotope studies. Research within radiocarbon dating has clearly demonstrated that species habitat preferences and ecology can impact the uptake ratio of ^{14}C from terrestrial and marine sources. This ratio affects the radiocarbon age and required calibration (ΔR correction) (Hogg et al., 1998; Petchey et al., 2012). Accurate identification can provide insights into environmental niches targeted for shell collection, and the ecological tolerances of identified taxa can help to define past environmental conditions (Peacock, 2000).

Identification of species present usually draws on both the published literature and reference collections. Given that shell identification books focus on colors, surface patterning, and overall shell morphology, such literature is not always immediately applicable to fragmented and taphonomically altered shell midden assemblages. Nevertheless, they can provide useful descriptions and pictures, as well as lists of the species occupying a particular biogeographic area or habitat to help constrain identifications. A reliable reference collection can be invaluable for more fine-grained comparison of specific shell features, angles, and surface textures. Variations in shell microstructure and internal composition, such as the presence of nacre, may also assist in identification. Depending on the state of preservation of an assemblage, identification to species level may not always be possible. In these instances, identification to genus or family will give the most accurate representation of assemblage contents.

Taxonomic nomenclature is an ever-shifting terrain, and many species names familiar to archaeologists may shift in and out of taxonomic validity. In addition to the most current literature, there are now a number of online resources providing the most up-to-date valid binomials for molluscan species (e.g., the World Register of Marine Species (WoRMS: http://www.marinespecies.org) and the Ocean Biogeographic Information System (OBIS: http://clade.ansp.org/obis/)). The presentation and discussion of taxonomic information should always follow zoological standards as outlined in the International Code of Zoological Nomenclature (International Commission on Zoological Nomenclature, 1999). Using the International Code of Zoological Nomenclature means that expression is standardized but also that scholars from the natural sciences can follow archaeological reporting with ease.

Sampling

There is no gold standard for the sampling of midden deposits. Instead, sampling strategies must be guided by the nature of the deposit and the research questions to be answered. If research questions are focused on paleoenvironmental reconstruction, then samples must be large enough to capture the diversity of species present, and techniques such as the flotation of sediments for land snail retrieval may prove valuable. For larger sites or deposits where spatiotemporal variation is a key issue, strategic core sampling to guide the selection of areas for further investigation can be productive.

A fundamental point about shell midden analyses was made by Claassen (1991) when she stated that sampling approaches during excavation are largely prefigured by the excavator's conceptions of what a midden *is*. The two ends of the spectrum are occupied by those who see shell middens as deflated and time-averaged dumps versus those who conceive of shell middens as the accretion of numerous discrete episodes of behavior. Claassen (1991, 254) associates limited exposures of the deposits and the use of arbitrary spits (levels) with the former and more extensive exposures and stratigraphic excavation with the latter. In a global context, this division is probably as accurate now as when Claassen originally published her paper titled "Normative thinking and shell-bearing sites." Nevertheless, thoughtful sampling strategies closely articulated with research questions have led to a number of productive approaches and discussions.

Given the sheer quantities of molluscan remains in many shell middens, column sampling represents an attractive way of covering considerable spatiotemporal variation while generating more manageable quantities of material. Such an approach was taken by Cannon (2000), whose interests lay in assessing regional patterning of shell midden deposits in Namu, British Columbia, as well as Martindale et al. (2009), who used percussion coring to assess the extent and chronostratigraphy of subsurface middens from insular British Columbia. The strengths of this approach lie in the ability to cover a wide range of terrain, to assess the spatial distribution of deposits in the landscape, and to collect material for radiocarbon dating. However, for studies that are focused at more spatially discrete levels, such as the site or site complex, larger midden samples are required to generate the fine-grained and more representative datasets required at this scale of investigation (e.g., see Estevez et al., 2001, for a comparison of sampling techniques).

The sheer size of many shell midden deposits can lead to questions about where the point of sampling redundancy may lie – although not as frequently as one might think. There have been various calculations and statements of the requisite sample required for the accurate representation of contents (e.g., Poteate and Fitzpatrick, 2013). Though such calculations may be accurate and well justified for particular sites, the combined variation in both deposits and research questions means that there can be no generally applicable number or formula.

Quantification

As with sampling strategies, there are various commonly used quantification techniques, each of which may be more or less applicable to various assemblages and research questions. Quantification by weight was favored in much of the early intensive midden research (see discussion in Mason et al., 1998), but distorting variables such as taphonomic loss of shell mass or the presence of concretions make accurate assessments of the relative contribution of different taxa difficult. Likewise, there is no easy correlation between shell weight and shell size/meat weight. There are certainly circumstances when weights can prove very useful – especially where total shell weights for different layers of a deposit are being compared – however count-based methods are now preferred for providing greater accuracy and comparability in assessing the composition and structure of shell midden assemblages.

The two major approaches to the numerical quantification of shell midden assemblages are recording the "number of identified specimens present" (NISP) and the "minimum number of individuals" represented (MNI). NISP is a taxa-based fragment count, where all shell fragments identified to a particular taxon are counted within each spit or layer. If there is differential fragmentation between taxa or areas within a site/deposit, this will necessarily result in skewed representation data, with inflated counts from the more fragmented species and locales. However, in some instances, such as when shell midden material is sparse within a deep sequence and/or highly fragmented, NISP quantification may be the only viable option. When combined with MNI quantification techniques, NISP counts can provide a valuable index of fragmentation.

MNI counts aim to calculate the minimum number of individual shells required to account for the excavated deposit. In traditional MNI analyses, all discrete, diagnostic elements of a shell present in an assemblage are counted, and the largest total per taxon per layer is taken as the MNI. In an alternative approach to MNI, a unique "non-repeating element" (NRE) is decided upon prior to analysis, and counts are made only of the occurrence of this element, whether it be a spire, aperture, hinge, or other distinctive feature. In the case of bivalves, left and right valves are counted separately, with the higher number taken to represent the MNI. For further discussion regarding the advantages and disadvantages of these two methods, see Giovas (2009). Underestimation of minimum numbers due to fragmentation is a recurring issue that some have addressed through the quantification of various categories of fragment types (e.g., Gutiérrez Zugasti, 2011).

The way in which midden deposits are excavated, and in particular whether they are excavated stratigraphically or using arbitrary spits, has flow-on consequences for the level of accuracy of MNI data. Grayson (1984) outlined in detail the "division into aggregates" problem as it relates to the quantification of vertebrate faunal remains. Where excavations have proceeded in arbitrary spits, different bones of the same animal may be in different spit assemblages, thus inflating counts when all spits are combined into an overall picture. A number of other issues with MNI are summarized in Lyman (2008). For the purposes of shell quantification, it should be stressed that many of these arguments apply minimally if at all. Since mollusks comprise far fewer individual, diagnostic parts than a vertebrate skeleton, it is much more difficult to inflate their counts by counting the same individual a number of times. Equally, the much lower rates of completely non-diagnostic fragments in shell, as compared to bone, assemblages means that NISP counts can easily be very inflated due to fragmentation. In short, the extensive standing arguments about the strengths and weaknesses of different quantification techniques must be thoughtfully adapted to molluscan shell, and, as ever, decisions should be based on the nature of the assemblage being studied and the research questions being addressed.

Research and analytical directions

Approaches to the study of midden shell assemblages are many and varied, but a few central themes of inquiry can be found consistently through the literature. These directions, and the analytical techniques with which they are commonly associated, are briefly discussed here.

Research direction: subsistence and diet

As shell middens are typically composed largely of the remains of meals, investigations into ancient subsistence and diet represent the core of the shell midden literature. The economic emphasis in shell midden analysis in the 1960s and 1970s placed a focus on the calculation of meat weights and assessments of the relative role(s) of shellfish in ancient diets (e.g., Shawcross, 1968; Bailey, 1975). Such detailed and data-rich work paved the way for foraging models that combined aspects of ecology and subsistence gathering (e.g., Anderson, 1981). Since these formative studies, investigations into the role of shellfish in diet and subsistence systems have grown and diversified in myriad directions worldwide. Such studies have also often been informed on some level by important ethnoarchaeological research.

The influential ethnoarchaeological study of shellfish gathering *Shell Bed to Shell Midden* by Meehan (1982) explicitly investigated the contribution of shellfish gathering by women among the Anbarra of northern Australia. While acknowledging that the contribution of shellfish was not substantial in terms of calories, Meehan stressed that shellfish were often gathered by members of society who were otherwise peripheral in subsistence activities: the very young and very old and women in advanced stages of pregnancy. She further pointed out the convenience, ease, and relative safety of shellfish gathering in contrast to other forms of food procurement. Such observations have been pivotal in the development of increasingly complex and nuanced considerations of the role of shellfish and shellfishing that weave in taphonomic, environmental, and visibility considerations (e.g., Dupont et al., 2007; van der Schriek et al., 2007; Porcasi, 2011).

Research direction: gathering strategies, metrics, and predation pressure

How people move and procure resources within a landscape was a central concern of the New Archaeology, and this manifested itself in shell midden studies as a concerted interest in gathering strategies (e.g., Voight, 1975; Anderson, 1981). The way in which people go about gathering a resource such as shellfish has implications not only for the finer structure of subsistence economies but also for mobility strategies and, in the longer term, the impact of human predation upon shell beds. Research into gathering strategies has continued steadily since the early work cited above, with recent explorations developing sophisticated approaches (e.g., Whitaker, 2008; Thakar, 2011).

A logical next step that grew out of this interest was investigation into potential human impact on molluscan resources. The twin themes of this literature are resource intensification and predation pressure, with the former often exploring the structure and composition of molluscan and/or faunal assemblages and the latter frequently using metrical tools to assess change.

Metrics-based analyses of shell midden assemblages have been a consistent presence in the literature, and they have often addressed the hypothesized relationship between shell size, predation intensity, and resource depression. However, such metrics-based studies can be complicated in shellfish where environmental factors can influence shell size and shape (e.g., Andrews et al., 1985; Peacock, 2000; Campbell, 2008). Also, the assumption that gatherers will selectively target the largest individuals of the largest species is only sometimes borne out (e.g., Anderson, 1981) and thus cannot be accepted a priori. Indeed, sometimes the harvesting of shellfish can lead to increases in growth rates, and hence age to size ratios, by providing more room and resources for the remaining shellfish through reduced competition (e.g., Swadling, 1976). Metrics-based approaches therefore need to be sensitive and attuned to the ecology and population dynamics of the species under discussion; a number of exemplary studies exist as guides (e.g., Swadling and Chowning, 1981; Jerardino, 1997; Faulkner, 2009, 2010). Several key ecological factors to consider when modeling the impacts of predation are presented by Catteral and Poiner (1987), with more general approaches to human impact considered by Keough and Quinn (1991).

Ethnoarchaeological studies have been central to generating frameworks for understanding not only human mollusk-gathering behavior and associated variables but also the impacts of these behaviors on the environment (Waselkov, 1987). In addition to Meehan's (1982) classic work discussed above, many ethnoarchaeological studies have investigated issues as diverse as the role of children in foraging (Bird and Bliege Bird, 2000), the gendered nature of marine exploitation (e.g., Malm, 2009), logistical foraging models (Thomas, 2002), and the impact of traditional foraging on littoral shell beds (Swadling and Chowning, 1981).

Research direction: paleoenvironmental reconstruction

In most cases, it is clear that shell middens have accumulated close to the habitats where the organisms originally flourished. Mollusks are bulky given the amount of flesh they yield, and while shells may move considerable distances as raw materials (e.g., Bar-Yosef Mayer, 1997; Dimitrijević and Tripković, 2006), ethnoarchaeological studies indicate that the gathering, processing, and disposal of shellfish tend to happen close to the place of collection (e.g., Meehan, 1982; Thomas, 2002). Spatial analyses considering the relationship of shell middens to paleoshorelines also support this pattern (e.g., Suguio et al., 1992; Ricklis and Blum, 1997). The general proximity of middens to coastal or freshwater habitats has led many analysts to use midden contents to infer aspects of past aquatic habitats. Stein (1992, 9) rightly points out that shell midden assemblages are inherently biased by cultural selection, meaning that caution must be exercised in extrapolating from midden contents to local habitats. Nevertheless, a bevy of techniques and approaches are increasingly helping shell midden analysts untangle the various contributions of cultural selection and local availability in their interpretations. Indeed, shell midden data can successfully act as a check on broader geoarchaeological interpretation (e.g., Morey and Crothers, 1998).

One of the key independent proxies for assessing environmental conditions is the analysis of stable isotopes locked within the structure of midden shells. Although a variety of stable isotopes can be analyzed to provide information on aspects of past environment, oxygen isotopes are the most commonly analyzed with shell midden samples. One of the most long-standing applications is the investigation of the season(s) of shell collection represented within a midden, conducted to inform about frequency of site use and group mobility (e.g., Kennett and Voorhies, 1996; Jones et al., 2008). Fine-grained studies combine sclerochronology, which analyzes the individual incremental growth bands laid down within the hard tissues of invertebrates and corals, with high precision oxygen isotope analysis (e.g., Quitmyer et al., 1997; Mannino et al., 2003; Burchell et al., 2013). Sclerochronological analysis in itself can yield information as to the age of shells at harvest and thus also inform about gathering strategies, harvest intensity, and resource management (e.g., Cannon and Burchell, 2009).

Despite the wide and successful use of oxygen isotope analysis within shell midden studies, there remain some points of caution to heed. Most notable is the fact that variability in $\delta^{18}O$ within water, and hence aquatic shell, is driven by both salinity and temperature. To counter this, some sensitive studies have also used parallel lines of analysis, such as Mg/Ca or Sr/Ca ratios, to disentangle variables (e.g., Schweikhardt et al., 2011). The use of multiple lines of evidence adds considerable weight to interpretations and helps resolve ambiguities (Peacock and Seltzer, 2008).

Research direction: chronometric applications

The most widely used chronometric techniques directly applied to archaeological shell are radiocarbon (^{14}C) approaches and amino acid racemization (AAR). Attempts to apply U-series techniques have been largely unsuccessful due to the "open-system" behavior of molluscan shell post-mortem, resulting in both the uptake and loss of uranium (see discussion in Eggins et al., 2005). However, new research into open-system techniques holds promise (Eggins et al., 2005). Research also continues into enhancing the reliability of electron spin resonance (ESR) techniques (Brumby and Yoshida, 1994; Molodkov, 2012).

When radiocarbon dating molluscan shell, several factors need to be taken into account. First, marine shell dates need to be corrected for the marine reservoir effect (MRE), and spatial variations can be further accounted for through the application of a locality-specific ΔR value (Ascough et al., 2007). The ecology and feeding habits of various species of mollusk can also result in the uptake of carbon from various sources, so careful sample selection with this in mind improves the reliability of radiocarbon dates (Hogg et al., 1998; Ascough et al., 2005; Petchey et al., 2012). Diagenetic recrystallization of the shell can also result in the incorporation of external carbon, so it is recommended to assess the structural integrity of the shell prior to dating (Yates, 1986).

Amino acid racemization has a long history within shell midden research, but persistent problems due to thermal effects on racemization rates – whether it be the temperature of the burial environment or exposure of the shell to burning – have hindered widespread application. The development of closed-system analysis, which investigates racemization of the intracrystalline fraction of the shell, overcomes these obstacles, opening up further possibilities for the use of AAR in shell midden archaeology (Penkman et al., 2008; Demarchi et al., 2011).

Summary

Despite the long history of shell midden analysis within archaeology, the twenty-first century has seen research questions diversify, the number of specialist analysts increase, and the application of scientific techniques to the study of shell middens expand and become more sophisticated. As key components of the archaeological landscape worldwide, shell middens can offer insights into human movement across the landscape, utilization of environmental resources, cultural and industrial practices, and the human impact on aquatic systems. The shells themselves preserve archives of past environmental conditions, which may be accessed through techniques such as stable isotope analyses, and archaeological shell is an important material for radiocarbon dating. Shell middens can create ideal microenvironments for the preservation of other archaeological materials. In other cases, the sensitivity of shells to a range of taphonomic processes can highlight aspects of the history of a site or deposit. As techniques in geoarchaeological and archaeological science continue to be refined, new ways of approaching old questions – such as the relative impacts of human predation and environmental change on molluscan populations in the past – will benefit from more sizeable and robust lines of evidence.

Bibliography

Allen, J., Holdaway, S., and Fullagar, R., 1997. Identifying specialisation, production and exchange in the archaeological record: the case of shell bead manufacture on Motupore Island, Papua. *Archaeology in Oceania*, **32**(1), 13–38.

Ambrose, R. F., 1983. Midden formation by octopuses: the role of biotic and abiotic factors. *Marine Behaviour and Physiology*, **10**(2), 137–144.

Anderson, A. J., 1981. A model of prehistoric collecting on the rocky shore. *Journal of Archaeological Science*, **8**(2), 109–120.

Anderson, A. J., 2005. Subpolar settlement in South Polynesia. *Antiquity*, **79**(306), 791–800.

Andrews, M. V., Gilbertson, D. D., Kent, M., and Mellars, P. A., 1985. Biometric studies of morphological variation in the intertidal gastropod *Nucella lapillus* (L): environmental and palaeoeconomic significance. *Journal of Biogeography*, **12**(1), 71–87.

Antczak, A. T., Posada, J. M., Shapira, D., Antczak, M. M., Cipriani, R., and Montaño, I. A., 2008. A history of human impact on the queen conch (*Strombus gigas*) in Venezuela. In Antczak, A. T., and Cipriani, R. (eds.), *Early Human Impact on Megamolluscs*. Oxford: Archaeopress. British Archaeological Reports, International Series 1865, pp. 49–64.

Ascough, P. L., Cook, G. T., Dugmore, A. J., Scott, E. M., and Freeman, S. P. H. T., 2005. Influence of mollusc species on marine DELTA R determinations. *Radiocarbon*, **47**(3), 433–440.

Ascough, P. L., Cook, G. T., Dugmore, A. J., and Scott, E. M., 2007. The North Atlantic marine reservoir effect in the early Holocene: implications for defining and understanding MRE values. *Nuclear Instruments and Methods in Physics Research B*, **259**(1), 438–447.

Attenbrow, V., 1991. Shell bed or shell midden. *Australian Archaeology*, **34**, 3–21.

Augustinus, P. G. E. F., 1989. Cheniers and chenier plains: a general introduction. *Marine Geology*, **90**(4), 219–229.

Bailey, G. N., 1975. The role of molluscs in coastal economies: the results of midden analysis in Australia. *Journal of Archaeological Science*, **2**(1), 45–62.

Bailey, G. N., 1977. Shell mounds, shell middens, and raised beaches in the Cape York Peninsula. *Mankind*, **11**(2), 132–143.

Bailey, G. N., 1991. Hens' eggs and cockle shells: Weipa shell mounds reconsidered. *Archaeology in Oceania*, **26**(1), 21–23.

Bailey, G. N., and Flemming, N. C., 2008. Archaeology of the continental shelf: marine resources, submerged landscapes and underwater archaeology. *Quaternary Science Reviews*, **27** (23–24), 2153–2165.

Bailey, G. N., Chappell, J., and Cribb, R., 1994. The origin of *Anadara* shell mounds at Weipa, North Queensland, Australia. *Archaeology in Oceania*, **29**(2), 69–80.

Barber, I., 2013. Molluscan mulching at the margins: investigating the development of a South Island Māori variation on Polynesian hard mulch agronomy. *Archaeology in Oceania*, **48**(1), 40–52.

Bar-Yosef Mayer, D. E., 1997. Neolithic shell bead production in Sinai. *Journal of Archaeological Science*, **24**(2), 97–111.

Beck, M. E., 2007. Midden formation and intrasite chemical patterning in Kalinga, Philippines. *Geoarchaeology*, **22**(4), 453–475.

Bird, D. W., and Bliege Bird, R., 2000. The ethnoarchaeology of juvenile foragers: shellfishing strategies among Meriam children. *Journal of Anthropological Archaeology*, **19**(4), 461–476.

Bocek, B., 1986. Rodent ecology and burrowing behavior: predicted effects on archaeological site formation. *American Antiquity*, **51**(3), 589–603.

Brumby, S., and Yoshida, H., 1994. ESR dating of mollusc shell: investigations with modern shell of four species. *Quaternary Science Reviews*, **13**(2), 157–162.

Burchell, M., Cannon, A., Hallmann, N., Schwarcz, H. P., and Schöne, B. R., 2013. Refining estimates for the season of shellfish collection on the Pacific Northeast Coast: applying high-resolution stable oxygen isotope analysis and sclerochronology. *Archaeometry*, **55**(2), 258–276.

Çakırlar, C., 2009. *Mollusk Shells in Troia, Yenibademli, and Ulucak: An Archaeomalacological Approach to the Environment and Economy of the Aegean*. Oxford: Archaeopress. British Archaeological Reports, International Series 2051.

Çakırlar, C., and Becks, R., 2009. Murex dye production at Troia: assessment of archaeomalacological data from old and new excavations. *Studia Troica*, **18**, 87–103.

Campbell, G., 2008. Beyond means to meaning: using distributions of shell shapes to reconstruct past collecting strategies. *Environmental Archaeology*, **13**(2), 111–121.

Cannon, A., 2000. Settlement and sea-levels on the central coast of British Columbia: evidence from shell midden cores. *American Antiquity*, **65**(1), 67–77.

Cannon, A., and Burchell, M., 2009. Clam growth-stage profiles as a measure of harvest intensity and resource management on the central coast of British Columbia. *Journal of Archaeological Science*, **36**(4), 1050–1060.

Carannante, A., 2011. Purple-dye industry shell waste recycling in the Bronze Age Aegean? Stoves and murex shells at Minoan Monastiraki (Crete, Greece). In Çakırlar, C. (ed.), *Archaeomalacology Revisited: Non-dietary Use of Molluscs in Archaeological Settings*. Oxford: Oxbow, pp. 9–18.
Catteral, C. P., and Poiner, I. R., 1987. The potential impact of human gathering on shellfish populations, with reference to some NE Australian intertidal flats. *Oikos*, **50**(1), 114–122.
Ceci, L., 1984. Shell midden deposits as coastal resources. *World Archaeology*, **16**(1), 62–74.
Chazottes, V., Le Campion-Alsumard, T., and Peyrot-Clausade, M., 1995. Bioerosion rates on coral reefs: interactions between macroborers, microborers and grazers (Moorea, French Polynesia). *Palaeogeography Palaeoclimatology Palaeoecology*, **113** (2–4), 189–198.
Christensen, C. C., and Kirch, P. V., 1981. Nonmarine mollusks from archaeological sites on Tikopia, southeastern Solomon Islands. *Pacific Science*, **35**(1), 75–88.
Cipriani, R., and Antczak, A. T., 2008. Qualitative effects of pre-Hispanic harvesting on queen conch: the tale of a structured matrix model. In Antczak, A. T., and Cipriani, R. (eds.), *Early Human Impact on Megamolluscs*. Oxford: Archaeopress. British Archaeological Reports, International Series 1865, pp. 95–110.
Claassen, C., 1991. Normative thinking and shell-bearing sites. In Schiffer, M. B. (ed.), *Archaeological Method and Theory.* Tucson: University of Arizona Press, Vol. 3, pp. 249–298.
Claassen, C., 1998. *Shells*. Cambridge: Cambridge University Press. Cambridge Manuals in Archaeology.
Claassen, C., 2010. The U.S. freshwater shell button industry. In Álvarez-Fernández, E., and Carvajal-Contreras, D. R. (eds.), *Not only Food: Marine, Terrestrial and Freshwater Molluscs in Archaeological Sites: Proceedings of the 2nd Meeting of the ICAZ Archaeomalacology Working Group (Santander, February 19th–22nd 2008).* Donostia: Sociedad de Ciencias/Aranzadi Zientzia Elkartea. Munibe Suplemento 31, pp. 302–309.
Demarchi, B., Williams, M. G., Milner, N., Russell, N., Bailey, G., and Penkman, K., 2011. Amino acid racemization dating of marine shells: a mound of possibilities. *Quaternary International*, **239**(1–2), 114–124.
Deshpande-Mukherjee, A., 2008. Archaeomalacological research in India with special reference to early historic exploitation of the sacred conch shell (*Turbinella pyrum*) in western Deccan. In Antczak, A. T., and Cipriani, R. (eds.), *Early Human Impact on Megamolluscs*. Oxford: Archaeopress. British Archaeological Reports, International Series 1865, pp. 209–222.
Dimitrijević, V., and Tripković, B., 2006. *Spondylus* and *Glycymeris* bracelets: trade reflections at neolithic Vinča-Belo Brdo. *Documenta Praehistorica*, **33**, 237–252.
Dupont, C., 2011. The dog whelk *Nucella lapillus* and dye extraction activities from the Iron age to the middle ages along the Atlantic coast of France. *Journal of Island and Coastal Archaeology*, **6**(1), 3–23.
Dupont, C., Schulting, R., and Tresset, A., 2007. Prehistoric shell middens along the French Atlantic façade: the use of marine and terrestrial resources in the diets of coastal human populations. In Milner, N., Craig, O. E., and Bailey, G. N. (eds.), *Shell Middens in Atlantic Europe*. Oxford: Oxbow, pp. 123–135.
Dwyer, P. G., Minnegal, M., and Thomson, J., 1985. Odds and ends: bower birds as taphonomic agents. *Australian Archaeology*, **21**, 1–10.
Edens, C., 1999. Khor Ile-Sud, Qatar: the archaeology of late bronze age purple-dye production in the Arabian Gulf. *Iraq*, **61**, 71–88.
Eggins, S. M., Grün, R., McCulloch, M. T., Pike, A. W. G., Chappell, J., Kinsley, L., Mortimer, G., Shelley, M., Murray-Wallace, C. V., Spötl, C., and Taylor, L., 2005. In situ U-series dating by laser-ablation multi-collector ICPMS: new prospects for quaternary geochronology. *Quaternary Science Reviews*, **24**(23–24), 2523–2538.
Erlandson, J. M., 1988. The role of shellfish in prehistoric economies: a protein perspective. *American Antiquity*, **53**(1), 102–109.
Erlandson, J. M., Rick, T. C., Collins, P. W., and Guthrie, D. A., 2007. Archaeological implications of a bald eagle nesting site at Ferrelo point, San Miguel Island, California. *Journal of Archaeological Science*, **34**(2), 255–271.
Estevez, J., Piana, E., Schiavini, A., and Juan-Muns, N., 2001. Archaeological analysis of shell middens in the Beagle Channel, Tierra del Fuego Island. *International Journal of Osteoarchaeology*, **11**(1–2), 24–33.
Evans, J. G., 1972. *Land Snails in Archaeology; With Special Reference to the British Isles*. London/New York: Seminar Press.
Faulkner, P., 2009. Focused, intense and long-term: evidence for granular ark (*Anadara granosa*) exploitation from late Holocene shell mounds of Blue Mud Bay, northern Australia. *Journal of Archaeological Science*, **36**(3), 821–834.
Faulkner, P., 2010. Morphometric and taphonomic analysis of granular ark (*Anadara granosa*) dominated shell deposits of Blue Mud Bay, northern Australia. *Journal of Archaeological Science*, **37**(8), 1942–1952.
Ford, P. J., 1992. Interpreting the grain size distributions of archaeological shell. In Stein, J. K. (ed.), *Deciphering a Shell Midden*. San Diego: Academic Press, pp. 283–325.
Gifford-Gonzales, D. P., Damrosch, D. B., Damrosch, D. R., Pryor, J., and Thunen, R. L., 1985. The third dimension in site structure: an experiment in trampling and vertical dispersal. *American Antiquity*, **50**(3), 803–818.
Giovas, C. M., 2009. The shell game: analytic problems in archaeological mollusc quantification. *Journal of Archaeological Science*, **36**(7), 1557–1564.
Godino, I. B., Álvarez, M., Balbo, A., Zurro, D., Madella, M., Villagrán, X., and French, C., 2011. Towards high-resolution shell midden archaeology: experimental and ethnoarchaeology in Tierra del Fuego (Argentina). *Quaternary International*, **239** (1–2), 125–134.
Graham, M. H., Dayton, P. K., and Erlandson, J. M., 2003. Ice ages and ecological transitions on temperate coasts. *Trends in Ecology and Evolution*, **18**(1), 33–40.
Grayson, D. K., 1984. *Quantitative Zooarchaeology: Topics in the Analysis of Archaeological Faunas*. Orlando: Academic Press.
Gutiérrez Zugasti, F. I., 2011. Shell fragmentation as a tool for quantification and identification of taphonomic processes in archaeomalacological analysis: the case of the Cantabrian region (northern Spain). *Archaeometry*, **53**(3), 614–630.
Habu, J., Matsui, A., Yamamoto, N., and Kanno, T., 2011. Shell midden archaeology in Japan: aquatic food acquisition and long-term change in the Jomon culture. *Quaternary International*, **239**(1–2), 19–27.
Ham, L. C., 1982. *Seasonality, Shell Midden Layers, and Coast Salish Subsistence Activities at the Crescent Beach Site, DgRr 1*. Unpublished Doctoral Thesis, University of British Columbia.
Hanagarth, W., 1993. *Acerca de la geoecología de las sabanas del Beni en el noreste de Bolivia*. La Paz: Instituto de Ecología.
Hanson, J. M., Mackay, W. C., and Prepas, E. E., 1989. Effect of size-selective predation by muskrats (*Ondatra zebithicus*) on a population of unionid clams (*Anodonta grandis simpsoniana*). *Journal of Animal Ecology*, **58**(1), 15–28.
Henderson, W. G., Anderson, L. C., and McGimsey, C. R., 2002. Distinguishing natural and archaeological deposits: stratigraphy, taxonomy, and taphonomy of Holocene shell-rich accumulations from the Louisiana Chenier Plain. *Palaios*, **17**(2), 192–205.
Henshilwood, C., Nilssen, P., and Parkington, J., 1994. Mussel drying and food storage in the late Holocene, SW Cape, South Africa. *Journal of Field Archaeology*, **21**(1), 103–109.

Hogg, A. G., Higham, T. F. G., and Dahm, J., 1998. ^{14}C dating of modern marine and estuarine shellfish. *Radiocarbon*, **40**(2), 975–984.

International Commission on Zoological Nomenclature. 1999. *International Code of Zoological Nomenclature*, 4th edn. London: The International Trust for Zoological Nomenclature, Natural History Museum. URL: http://www.nhm.ac.uk/hosted-sites/iczn/code/

Jerardino, A., 1997. Changes in shellfish species composition and mean shell size from a late-Holocene record of the west coast of Southern Africa. *Journal of Archaeological Science*, **24**(11), 1031–1044.

Jerardino, A., 2012. Large shell middens and hunter-gatherer resource intensification along the west coast of South Africa: the Elands Bay case study. *Journal of Island and Coastal Archaeology*, **7**, 76–101.

Jerardino, A., and Navarro, R., 2008. Shell morphometry of seven limpet species from coastal shell middens in southern Africa. *Journal of Archaeological Science*, **35**(4), 1023–1029.

Jones, R., and Allen, J., 1978. Caveat excavator: a sea bird midden on Steep Head Island, north west Tasmania. *Australian Archaeology*, **8**, 142–145.

Jones, T. L., Kennett, D. J., Kennett, J. P., and Codding, B. F., 2008. Seasonal stability in late Holocene shellfish harvesting on the central California coast. *Journal of Archaeological Science*, **35**(8), 2286–2294.

Keegan, W. F., 1984. Pattern and process in *Strombus gigas* tool replication. *Journal of New World Archaeology*, **6**(2), 15–25.

Kennett, D. J., and Voorhies, B., 1996. Oxygen isotope analysis of archaeological shells to detect seasonal use of wetlands on the southern Pacific coast of Mexico. *Journal of Archaeological Science*, **23**(5), 689–704.

Keough, M. J., and Quinn, G. P., 1991. Causality and the choice of measurements for detecting human impacts in marine environments. *Australian Journal of Marine and Freshwater Research*, **42**(5), 539–554.

Kidwell, S. M., and Holland, S. M., 1991. Field description of coarse bioclastic fabrics. *Palaios*, **6**(4), 426–434.

Kidwell, S. M., Fürsich, F. T., and Aigner, T., 1986. Conceptual framework for the analysis and classification of fossil concentrations. *Palaios*, **1**(3), 228–238.

Koike, H., 1979. Seasonal dating and the valve-pairing technique in shell-midden analysis. *Journal of Archaeological Science*, **6**(1), 63–74.

Koren, Z. C., 2005. The first optimal all-Murex all-natural purple dyeing in the Eastern Mediterranean in a millennium and a half and its colorimetric characterization. In Kirby, J. (ed.), *Dyes in History and Archaeology 20*. London: Archetype Publications, pp. 136–149.

Kowalewski, M., and Labarbera, M., 2004. Actualistic taphonomy: death, decay, and disintegration in contemporary settings. *Palaios*, **19**(5), 423–427.

Langstroth Plotkin, R., 1996. *Forest Islands in an Amazonian Savanna of Northeastern Bolivia*. Unpublished PhD thesis, University of Wisconsin-Madison.

Lombardo, U., Szabó, K., Capriles, J. M., May, J.-H., Amelung, W., Hutterer, R., Lehndorff, E., Plotzki, A., and Veit, H., 2013. Early and middle Holocene hunter-gatherer occupations in western Amazonia: the hidden shell middens. *PLoS One*, **8**(8), e72746, doi:10.1371/journal.pone.0072746.

Lubell, D., 2004. Prehistoric edible land snails in the circum-Mediterranean: the archaeological evidence. In Brugal, J.-P., and Desse, J. (eds.), *Petits animaux et sociétés humaines. Du complément alimentaire aux ressources utilitaires, XXIVe rencontres internationales d'archéologie et d'histoire d'Antibes*. Antibes: Éditions APCDA, pp. 77–98.

Lubell, D., Hassan, F. A., Gautier, A., and Ballais, J.-L., 1976. The Capsian escargotières: an interdisciplinary study elucidates Holocene ecology and subsistence in North Africa. *Science*, **191**(4230), 910–920.

Lyman, R. L., 2008. *Quantitative Paleozoology*. Cambridge: Cambridge University Press.

Malm, T., 2009. Women of the coral gardens: the significance of marine gathering in Tonga. *SPC*, **25**, 2–15. Traditional Marine Resource Management and Knowledge Information Bulletin.

Mannino, M. A., Spiro, B. F., and Thomas, K. D., 2003. Sampling shells for seasonality: oxygen isotope analysis on shell carbonates of the inter-tidal gastropod *Monodonta lineata* (da Costa) from populations across its modern range and from a Mesolithic site in southern Britain. *Journal of Archaeological Science*, **30**(6), 667–679.

Marquardt, W. H., 2010. Shell mounds in the Southeast: middens, monuments, temple mounds, rings, or works? *American Antiquity*, **75**(3), 551–570.

Martindale, A., Letham, B., McLaren, D., Archer, D., Burchell, M., and Schöne, B. R., 2009. Mapping of subsurface shell midden components through percussion coring: examples from the Dundas Islands. *Journal of Archaeological Science*, **36**(7), 1565–1575.

Mason, R. D., Peterson, M. L., and Tiffany, J. A., 1998. Weighing vs. counting: measurement reliability and the California school of midden analysis. *American Antiquity*, **63**(2), 303–324.

Medway, L., 1960. Niah Shell – 1954–8 (a preliminary report). *Sarawak Museum Journal*, **9**(15–16 new series), 368–379.

Meehan, B., 1977. Man does not live by calories alone: the role of shellfish in coastal cuisine. In Allen, J., Golson, J., and Jones, R. (eds.), *Sunda and Sahul: Prehistoric Studies in Southeast Asia, Melanesia and Australia*. New York: Academic Press, pp. 493–531.

Meehan, B., 1982. *Shell Bed to Shell Midden*. Canberra: Australian Institute of Aboriginal Studies.

Miracle, P. T., 1995. *Broad-Spectrum Adaptations Re-examined: Hunter-Gatherer Responses to Late Glacial Environmental Changes in the Eastern Adriatic*. Unpublished PhD thesis, University of Michigan.

Moholy-Nagy, H., 1997. Middens, construction fill, and offerings: evidence for the organization of classic period craft production at Tikal, Guatemala. *Journal of Field Archaeology*, **24**(3), 293–313.

Molodkov, A., 2012. Cross-check of the dating results obtained by ESR and IR-OSL methods: implication for the Pleistocene palaeoenvironmental reconstructions. *Quaternary Geochronology*, **10**, 188–194.

Morey, D. F., and Crothers, G. M., 1998. Clearing up clouded waters: palaeoenvironmental analysis of freshwater mussel assemblages from the Green River shell middens, western Kentucky. *Journal of Archaeological Science*, **25**(9), 907–926.

Morrison, M., 2013. Niche production strategies and shell matrix site variability at Albatross Bay, Cape York Peninsula. *Archaeology in Oceania*, **48**(2), 78–91.

Muckle, R. J., 1985. *Archaeological Considerations of Bivalve Shell Taphonomy*. Unpublished MA thesis, Simon Fraser University.

Nigra, B. T., and Arnold, J. E., 2013. Explaining the monopoly in shell-bead production on the channel Islands: drilling experiments with four lithic raw materials. *Journal of Archaeological Science*, **40**(10), 3647–3659.

Nixon, M., Maconnachie, E., and Howell, P. G. T., 1980. The effects on shells of drilling by *Octopus*. *Journal of Zoology (London)*, **191**(1), 75–88.

Onat, A. R. B., 1985. The multifunctional use of shellfish remains: from garbage to community engineering. *Northwest Anthropological Research Notes*, **19**(2), 201–207.

Panda, A., and Misra, M. K., 2007. Traditional methods of mollusc shell collection for lime preparation in East coast of India. *Indian Journal of Traditional Knowledge*, **6**(4), 549–558.

Parkington, J., 2012. Mussels and mongongo nuts: logistical visits to the Cape west coast, South Africa. *Journal of Archaeological Science*, **39**(5), 1521–1530.

Peacock, E., 2000. Assessing bias in archaeological shell assemblages. *Journal of Field Archaeology*, **27**(2), 183–196.

Peacock, E., and Seltzer, J. L., 2008. A comparison of multiple proxy data sets for paleoenvironmental conditions as derived from freshwater bivalve (Unionid) shell. *Journal of Archaeological Science*, **35**(9), 2557–2565.

Penkman, K. E. H., Kaufman, D. S., Maddy, D., and Collins, M. J., 2008. Closed-system behaviour of the intra-crystalline fraction of amino acids in mollusc shells. *Quaternary Geochronology*, **3**(1–2), 2–25.

Petchey, F., Ulm, S., David, B., McNiven, I. J., Asmussen, B., Tomkins, H., Richards, T., Rowe, C., Leavesley, M., Mandui, H., and Stanisic, J., 2012. ^{14}C marine reservoir variability in herbivores and deposit-feeding gastropods from an open coastline, Papua New Guinea. *Radiocarbon*, **54**(3–4), 967–978.

Peterson, N., 1973. Camp-site location amongst Australian hunter-gatherers: archaeological and ethnographic evidence for a key determinant. *Archaeology and Physical Anthropology in Oceania*, **8**(3), 173–193.

Piperno, D. R., 1985. Phytolith taphonomy and distributions in archeological sediments from Panama. *Journal of Archaeological Science*, **12**(4), 247–267.

Porcasi, J. F., 2011. More on mollusks: trans-Holocene shellfish exploitation on the California coast. *Journal of Island and Coastal Archaeology*, **6**(3), 398–420.

Poteate, A. S., and Fitzpatrick, S. M., 2013. Testing the efficacy and reliability of common zooarchaeological sampling strategies: a case study from the Caribbean. *Journal of Archaeological Science*, **40**(10), 3693–3705.

Quitmyer, I. R., Jones, D. S., and Arnold, W. S., 1997. The sclerochronology of hard clams, *Mercenaria* spp., from the South-Eastern U.S.A.: a method of elucidating the zooarchaeological records of seasonal resource procurement and seasonality in prehistoric shell middens. *Journal of Archaeological Science*, **24**(9), 825–840.

Rabett, R., Appleby, J., Blyth, A., Farr, L., Gallou, A., Griffiths, T., Hawkes, J., Marcus, D., Marlow, L., Morley, M., Nguyễn, C. T., Nguyễn, V. S., Penkman, K., Reynolds, T., Stimpson, C., and Szabó, K., 2011. Inland shell midden site-formation: investigation into a late Pleistocene to early Holocene midden from Tràng An, Northern Vietnam. *Quaternary International*, **239**(1–2), 153–169.

Reese, D. S., 1980. Industrial exploitation of *Murex* shells: purple-dye and lime production at Sidi Khrebish, Benghazi (Berenice). *Libyan Studies*, **11**, 79–93.

Reese, D. S., 2010. Shells from Sarepta (Lebanon) and East Mediterranean purple-dye production. *Mediterranean Archaeology and Archaeometry*, **10**(1), 113–141.

Rick, T. C., 2002. Eolian processes, ground cover, and the archaeology of coastal dunes: a taphonomic case study from San Miguel Island, California, U.S.A. *Geoarchaeology*, **17**(8), 811–833.

Ricklis, R. A., and Blum, M. D., 1997. The geoarchaeological record of Holocene sea level change and human occupation of the Texas Gulf coast. *Geoarchaeology*, **12**(4), 287–314.

Ronen, A., 1980. The origin of the raised pelecypod beds along the Mediterranean coast of Israel. *Paléorient*, **6**, 165–172.

Rosendahl, D., Ulm, S., and Weisler, M. I., 2007. Using foraminifera to distinguish between natural and cultural shell deposits in coastal eastern Australia. *Journal of Archaeological Science*, **34**(10), 1584–1593.

Ruscillo, D., 2005. Reconstructing *murex* royal purple and biblical blue in the Aegean. In Bar-Yosef Mayer, D. (ed.), *Archaeomalacology: Molluscs in Former Environments of Human Behaviour*. Oxford: Oxbow Books, pp. 99–106.

Saunders, R., and Russo, M., 2011. Coastal shell middens in Florida: a view from the Archaic period. *Quaternary International*, **239**(1–2), 38–50.

Schweikhardt, P., Ingram, B. L., Lightfoot, K., and Luby, E., 2011. Geochemical methods for inferring seasonal occupation of an estuarine shellmound: a case study from San Francisco Bay. *Journal of Archaeological Science*, **38**(9), 2301–2312.

Serrand, N., and Bonnissent, D., 2005. Pre-columbian Preceramic shellfish consumption and shell tool production: shell remains from Orient Bay, Saint Martin, Northern Lesser Antilles. In Bar-Yosef Mayer, D. (ed.), *Archaeomalacology: Molluscs in Former Environments of Human Behaviour*. Oxford: Oxbow Books, pp. 29–39.

Shawcross, W., 1968. An investigation of prehistoric diet and economy on a coastal site at Galatea Bay, New Zealand. *Proceedings of the Prehistoric Society*, **33**, 107–131.

Shillito, L.-M., and Matthews, W., 2013. Geoarchaeological investigations of midden-formation processes in the early to late ceramic Neolithic levels at Çatalhöyük, Turkey *ca.* 8550–8370 cal BP. *Geoarchaeology*, **28**(1), 25–49.

Shillito, L.-M., Matthews, W., Almond, M. J., and Bull, I. D., 2011. The microstratigraphy of middens: capturing daily routine in rubbish at neolithic Çatalhöyük, Turkey. *Antiquity*, **85**(329), 1024–1038.

Silliman, B. R., Layman, C. A., Geyer, K., and Zieman, J. C., 2004. Predation by the black-clawed mud crab, *Panopeus herbstii*, in Mid-Atlantic salt marshes: further evidence for top-down control of marsh grass production. *Estuaries*, **27**(2), 188–196.

Spanier, E., 1986. Cannibalism in muricid snails as a possible explanation for archaeological findings. *Journal of Archaeological Science*, **13**(5), 463–468.

Specht, J., 1985. Crabs as disturbance factors in tropical archaeological sites. *Australian Archaeologist*, **21**, 11–18.

Stanner, W. E. H., 1961. The Weipa shell-mounds. *The Etruscan*, **11**, 8–12.

Stein, J. K., 1983. Earthworm activity: a source of potential disturbance of archaeological sediments. *American Antiquity*, **48**(2), 277–289.

Stein, J. K., 1992. *Deciphering a Shell Midden*. San Diego: Academic Press.

Stein, J. K., Deo, J. N., and Phillips, L. S., 2003. Big sites – short time: accumulation rates in archaeological sites. *Journal of Archaeological Science*, **30**(3), 297–316.

Stone, T., 1989. Origins and environmental significance of shell and earth mounds in Northern Australia. *Archaeology in Oceania*, **24**(2), 59–64.

Stone, T., 1991. Two birds with one stone: a reply. *Archaeology in Oceania*, **26**(1), 26–28.

Stone, T., 1995. Shell mound formation in coastal northern Australia. *Marine Geology*, **129**(1–2), 77–100.

Suguio, K., Martin, L., and Flexor, J.-M., 1992. Paleoshorelines and the sambaquis of Brazil. In Johnson, L. L., and Stright, M. (eds.), *Paleoshorelines and Prehistory: An Investigation of Method*. Boca Raton: CRC Press, pp. 83–99.

Swadling, P., 1976. Changes induced by human exploitation in prehistoric shellfish populations. *Mankind*, **10**(3), 156–162.

Swadling, P., and Chowning, A., 1981. Shellfish gathering at Nukalau Island, West New Britain Province, Papua New Guinea. *Journal de la Société des océanistes*, **37**(72–73), 159–167.

Szabó, K., 2012. Terrestrial hermit crabs (Anomura: Coenobitidae) as taphonomic agents in circum-tropical coastal sites. *Journal of Archaeological Science*, **39**(4), 931–941.

Szabó, K., (2015). Molluscan remains from the Niah Caves. In: Barker, G. (ed.), *Rainforest Foraging and Farming in Island Southeast Asia: The Archaeology of the Niah Caves, Sarawak* . Vol. 2, Cambridge: McDonald Institute Monographs
Szabó, K., Ramirez, H., Anderson, A., and Bellwood, P., 2003. Prehistoric subsistence strategies on the Batanes Islands, northern Philippines. *Bulletin of the Indo-Pacific Prehistory Association*, **23**, 163–171.
Taylor, V. K., Barton, R. N. E., Bell, M., Bouzouggar, A., Collcutt, S., Black, S., and Hogue, J. T., 2011. The Epipalaeolithic (Iberomaurusian) at Grotte des Pigeons (Taforalt), Morocco: a preliminary study of the land Mollusca. *Quaternary International*, **244**(1), 5–14.
Thakar, H. B., 2011. Intensification of shellfish exploitation: evidence of species-specific deviation from traditional expectations. *Journal of Archaeological Science*, **38**(10), 2596–2605.
Thomas, F. R., 2002. An evaluation of central-place foraging among mollusk gatherers in Western Kiribati, Micronesia: linking behavioral ecology with ethnoarchaeology. *World Archaeology*, **34**(1), 182–208.
Trinkley, M., 1985. The form and function of South Carolina's early Woodland shell rings. In Dickens, R. S., Jr., and Ward, H. T. (eds.), *Structure and Process in Southeastern Archaeology*. Tuscaloosa: University of Alabama Press, pp. 102–118.
Van der Schriek, T., Passmore, D. G., Stevenson, A. C., and Rolão, J. M., 2007. The influence of environmental change on Mesolithic settlement-subsistence and shell midden formation along the lower Tagus River, Portugal. In Milner, N., Craig, O. E., and Bailey, G. N. (eds.), *Shell Middens in Atlantic Europe*. Oxford: Oxbow Books, pp. 165–182.
Verdún, E., 2010. Molluscs as sedimentary components. Another perspective of analysis. In: Álvarez-Fernández, E., and Carvajal-Contreras, D. R. (eds.), *Not only Food: Marine, Terrestrial and Freshwater Molluscs in Archaeological Sites: Proceedings of the 2nd Meeting of the ICAZ Archaeomalacology Working Group (Santander, February 19th–22nd 2008)*, Donostia: Sociedad de Ciencias/Aranzadi Zientzia Elkartea. Munibe Suplemento 31, pp. 294–301.
Vermeij, G. J., 1995. *A Natural History of Shells*. Princeton: Princeton University Press.
Villagran, X. S., Giannini, P. C. F., and DeBlasis, P., 2009. Archaeofacies analysis: using depositional attributes to identify anthropic processes of deposition in a monumental shell mound of Santa Catarina State, southern Brazil. *Geoarchaeology*, **24**(3), 311–335.
Villagran, X. S., Balbo, A. L., Madella, M., Vila, A., and Estevez, J., 2011a. Stratigraphic and spatial variability in shell middens: Microfacies identification at the ethnohistoric site Tunel VII (Tierra del Fuego, Argentina). *Archaeological and Anthropological Sciences*, **3**(4), 357–378.
Villagran, X. S., Klokler, D., Peixoto, S., DeBlasis, P., and Giannini, P. C. F., 2011b. Building coastal landscapes: zooarchaeology and geoarchaeology of Brazilian shell mounds. *Journal of Island and Coastal Archaeology*, **6**(2), 211–234.
Voight, E., 1975. Studies of marine mollusca from archaeological sites: dietary preferences, environmental reconstructions and ethnological parallels. In Clason, A. T. (ed.), *Archaeozoological Studies*. Amsterdam: North-Holland, pp. 87–98.
Wagner, G., Hilbert, K., Bandeira, D., Tenório, M. C., and Okumura, M. M., 2011. *Sambaquis* (shell mounds) of the Brazilian coast. *Quaternary International*, **239**(1–2), 51–60.
Wandsnider, L., 1988. Experimental investigation of the effect of dune processes on archaeological remains. *American Archaeology*, **7**(1), 18–29.
Waselkov, G. A., 1987. Shellfish gathering and shell midden archaeology. *Advances in Archaeological Method and Theory*, **10**, 93–210.
Whitaker, A. R., 2008. Incipient aquaculture in prehistoric California?: long-term productivity and sustainability vs. immediate returns for the harvest of marine invertebrates. *Journal of Archaeological Science*, **35**(4), 1114–1123.
Widmer, R. J., 1989. Archaeological Research Strategies in the Investigation of Shell-Bearing Sites, a Florida Perspective. Paper presented at the Annual Meeting of the Society for American Archaeology, Atlanta
Williams, M. B., and Bendremer, J., 1997. The archaeology of maize, pots, and seashells: gender dynamics in late Woodland and contact period New England. In Claassen, C., and Joyce, R. A. (eds.), *Women in Prehistory: North America and Mesoamerica*. Philadelphia: University of Pennsylvania Press, pp. 136–149.
Woodroffe, C. D., and Grime, D., 1999. Storm impact and evolution of a mangrove-fringed chenier plain, Shoal Bay, Darwin, Australia. *Marine Geology*, **159**(1–4), 303–321.
Yates, T., 1986. Studies of non-marine mollusks for the selection of shell samples for radiocarbon dating. *Radiocarbon*, **28**(2A), 457–463.
Yerkes, R. W., 1989a. Shell bead production and exchange in prehistoric Mississippian populations. In Hayes, C. F., Ceci, L., and Bodner, C. C. (eds.), *Proceedings of the 1986 Shell Bead Conference: Selected Papers*. Rochester: Rochester Museum and Science Center, pp. 113–123.
Yerkes, R. W., 1989b. Mississippian craft specialization on the American bottom. *Southeastern Archaeology*, **8**(2), 93–106.
Zuschin, M., Stachowitsch, M., and Stanton, R. J., Jr., 2003. Patterns and processes of shell fragmentation in modern and ancient marine environments. *Earth Science Reviews*, **63**(1–2), 33–82.

Cross-references

Amino Acid Racemization
Coastal Settings
Oxygen Isotopes
Paleodiet
Paleoenvironmental Reconstruction
Paleoshores (Lakes and Sea)
Radiocarbon Dating
Site Formation Processes
Site Preservation
Trampling

SHIPWRECK GEOARCHAEOLOGY

Rory Quinn
Centre for Maritime Archaeology, School of Environmental Sciences, University of Ulster, Coleraine, Northern Ireland, UK

Introduction

The past two decades have witnessed remarkable advances in seafloor mapping, with high-resolution acoustic imaging now routinely used in archaeological studies (e.g., Plets et al., 2011; Westley et al., 2011). Technological and methodological advances in acoustic imaging and digital rendering now permit shipwreck sites and individual artifacts to be imaged at centimetric resolution in tens or hundreds of meters of water (Quinn et al., 2005). Beyond using acoustics as merely a prospection tool for locating wreck sites, researchers are increasingly exploiting the quantitative aspects of these data, for example, using time-lapse multi-beam echo-sounder (MBES) bathymetric surveys to develop accretion-erosion plots (Quinn and Boland, 2010) and using MBES backscatter data to identify shipwrecks remotely (Masetti and Calder, 2012).

In response to the 1992 Valetta European Convention on the Protection of the Archaeological Heritage and the 2001 UNESCO Convention on the Protection of the Underwater Cultural Heritage, maritime archaeologists are encouraged to adopt nondestructive techniques for wreck investigations and consider in situ preservation as a priority (Plets, 2013). Therefore, marine geophysical techniques are playing an increasingly important role in shipwreck archaeology. They offer rapid, noninvasive, high-resolution, and cost-effective solutions in all phases of wreck investigations – from initially locating the site (Plets et al., 2011) to characterizing the site (Smyth and Quinn, 2014) and finally, managing the site (Quinn and Boland, 2010).

Shipwreck prospection

Shipwreck prospection refers to the noninvasive search for submerged and buried shipwreck sites using marine geophysical (primarily acoustic and magnetic) techniques.

Navigation and positioning

Tight navigational and positional control is essential in all phases of shipwreck investigation. To locate features and objects on the seabed precisely, we need to know where the survey vessel is located on the sea surface, where the sonar platform is located below the sea surface, and which portion of the seafloor is being radiated or sampled at any given time. This control is achieved through a combination of position fixing (latitude, longitude, and altitude above a reference datum), heading, speed, and attitude (heave, roll, pitch, yaw) information.

The minimum requirement for accurate navigation of a survey vessel is the Global Positioning System (GPS). Using the calculated distance and orbital position of a minimum of three satellites, a GPS receiver determines position in degrees of latitude and longitude, conventionally to the WGS84 datum (World Geodetic System of 1984, the default datum for GPS units). This position can subsequently be translated into any global or local metric coordinate system (e.g., UTM). Accuracy of GPS varies with satellite constellation geometry and receiver type, but an accuracy of ±5 m with an update rate of 1 Hz is common. To reduce positional errors to an acceptable level for high-resolution archaeological surveys (±1 m), differential GPS (DGPS) uses a land station to calculate the error in positioning and transmits the error to the shipboard receiver.

For quantitative analysis of the seafloor and/or its subsurface, it is essential to relate depth data to a fixed horizon, and therefore, it is necessary to remove the effects of tidal variation over the survey period. Tidal corrections are achieved with reference to either a static tidal gauge or modeled tidal predictions. For high-accuracy surveys, the tidal curve should be recorded continuously at a site in close proximity (±1 km) to the survey site.

Recently, DGPS has been superseded by Real Time Kinematic (RTK) systems that use the characteristics of the signal carrying the GPS data from satellite to receiver to give horizontal position and vertical altitudes to an accuracy of ±1 cm. Tidal corrections can be derived from the vertical component of the RTK signal, eliminating the need for a static tide gauge.

The position of the remote sensing platform (sometimes hull-mounted and sometimes towed) is determined in one of two ways: either by manual calculation or by acoustic tracking. The portion of the seafloor insonified at any given time is addressed by measuring the motion of the survey platform using an Inertial Measurement Unit (IMU) or Motion Referencing Unit (MRU). This system uses a combination of accelerometers and gyroscopes to track vessel movement. These corrections are applied to remotely sensed data to correct for the effects of pitch, roll, and yaw on the survey vessel and/or towfish (the transmitting instrument towed beneath the sea surface by a survey vessel).

Acoustic prospection methods

A comprehensive discussion on ocean acoustics and instrumentation is beyond the scope of this entry. However, a basic understanding of these concepts is essential to interpret acoustic data collected for archaeological purposes. For a more comprehensive treatment of the subject, Lurton (2010) is recommended. Additionally, review chapters on acoustic remote sensing in maritime archaeology (Quinn, 2011), and underwater survey and acoustic characterization of archaeological materials (Plets, 2013) provide further recommended reading.

Acoustic remote sensing methods rely on the propagation of acoustic waves by mechanical perturbation through an elastic medium (i.e., a gas, liquid, or solid). The mechanical properties of the propagating medium dictate the velocity of the acoustic pulse. In seawater, the acoustic wave velocity (v) typically varies from 1,450 to 1,550 ms^{-1} and is dependent on pressure, salinity, and temperature (Lurton, 2010). Seawater density (ρ) is typically 1,030 kgm^{-3} and is dependent on the same physical parameters as velocity. In conventional acoustic surveys, the acoustic transducer at the sea surface propagates a vertical sound wave to the seafloor and measures the time taken for the wave to travel down, reflect off the seabed (or subsurface target), and travel back to the transducer (the two-way travel time or twt). Depth/distance (d) and time are related:

$$d = \frac{v.twt}{2}$$

Acoustic signals are characterized by their frequency (f, measured in Hz) and period (T, measured in s), where T = 1/f. The frequencies used in active underwater acoustics typically range from 1 Hz to 1 MHz, with source choice dependent on application, water depth, and resolution required. Wavelength (λ, measured in m) is the spatial equivalent of wave period and corresponds to the distance traveled by the wave during one period of the signal with velocity v:

$$\lambda = vT = \frac{v}{f}$$

Typically objects are resolved at one quarter the wavelength of the acoustic source. So, for example, for a sound velocity of 1,500 ms^{-1}, a 1 kHz source will resolve an object larger than 0.375 m, and a 100 kHz source will resolve an object larger than 0.004 m. Two of the main constraints on the usable frequencies for a particular application are acoustic wave attenuation in the water column (energy loss due to viscosity in the propagating medium) and source directivity (the directional effectiveness of the sound source) (see Lurton, 2010). High-frequency acoustic sources are preferred for their resolution and directivity, but high frequencies are attenuated more readily and therefore travel only short distances. This implies compromise and a challenge in terms of survey design and instrument choice.

The transmitted acoustic pulse may be deflected in many ways as it propagates through the water column and seabed subsurface; it may encounter air bubbles, fish, suspended sediment, rough seafloors, and subsurface targets. In each case, a proportion of the sound is *reflected* and *scattered* in various directions, including back toward the survey instrument. Specular reflection is caused by plane interfaces – that is, the incident wave is reflected in a direction symmetrical to the direction of arrival (like light off a mirror), with a loss of amplitude (Lurton, 2010). Scattering is generally caused by rough interfaces and discrete objects in the water column and at the seafloor. The ratio between reflected and scattered contributions decreases at higher frequencies (Lurton, 2010).

In terms of subsurface reflection, materials are characterized by their density and velocity, where the product of the two is termed acoustic impedance (Z):

$$Z = \rho v$$

The strength of the reflection from the boundary between two materials of acoustic impedance Z_1 and Z_2 (a measure of the proportion of energy returned toward the survey instrument) is governed by the reflection coefficient (K_R), where

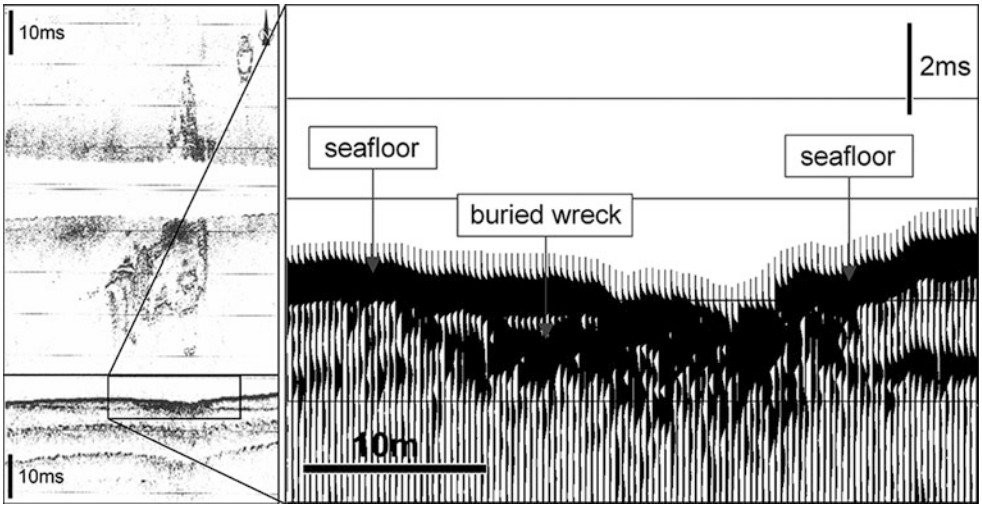
$$K_R = \frac{Z_2 - Z_1}{Z_2 + Z_1} = \frac{\rho_2 v_2 - \rho_1 v_1}{\rho_2 v_2 + \rho_1 v_1}$$

Put simply, this equation means that the higher the contrast in density and/or velocity across the material boundary, the stronger the reflection from the interface. The polarity of the reflection coefficient is dependent on whether there is an increase (positive reflection) or decrease (negative reflection) in the acoustic impedance across the interface.

Acoustic methods fall into two broad categories: profiling methods (which rely on specular reflection and image a narrow profile of the seabed directly beneath the sonar) and swath methods (which rely on scattering and image a wide corridor on either side of the sonar). Swath devices are more effective for regional-scale prospection surveys as they cover larger areas of the seafloor and result in less survey effort, saving time and money.

The most common profiling methods employed in archaeology are single-beam echo-sounders (SBES) and sub-bottom profilers (SBP). Inexpensive SBES are now commonplace, with many vessels equipped to conduct relatively unsophisticated but effective low-resolution bathymetric surveys. SBES systems consist of single hull-mounted or pole-mounted transceivers that transmit single- or dual-frequency pulses, typically within the 50–300 kHz bandwidth. The frequency-dependent, vertical resolution of these systems can be as great as a few centimeters. The pulse, with a 30–45° cone angle, is oriented vertically downward, concentrating the acoustic energy in a small circular area of the seabed (the radius of this circle is dependent on the water depth). Analysis of the return can also provide information on seabed type. The same system is routinely used to detect targets in the water column (fishers commonly refer to SBES as "fish finders"). The horizontal resolution of SBES systems is controlled by a combination of source frequency, cone angle, and water depth. For example, a 200 kHz echo-sounder with a 50° cone angle has a horizontal resolution of 0.14 m in a water depth of 20 m. A disadvantage of SBES systems is that the density of the survey grid controls the effective horizontal resolution of the survey data. In a tidal environment, the maximum survey grid density achievable is on the order of 5 m. Therefore, the highest possible horizontal resolution for the bathymetric survey is ±5 m. Bathymetric data are conventionally represented as profiles, two-dimensional contour plots, or three-dimensional digital elevation models (DEMs). Regional-scale SBES surveys are normally designed with survey lines oriented perpendicular to the coast, as bathymetric variation is usually at a maximum in this direction. Site-specific SBES surveys are conventionally designed with survey lines oriented on a grid.

As many archaeological sites coincide with areas of high sedimentation, partial or complete burial of shipwrecks is common. When nonmetallic sites are buried, the only technique suitable for detecting them is sub-bottom (seismic) profiling (Bull et al., 1998; Plets et al., 2008). These systems produce vertical and three-dimensional pseudo cross sections of the subsurface sediments and buried archaeological material. SBPs operate on similar principles to SBES, but they transmit lower frequencies, allowing them to penetrate the seafloor and

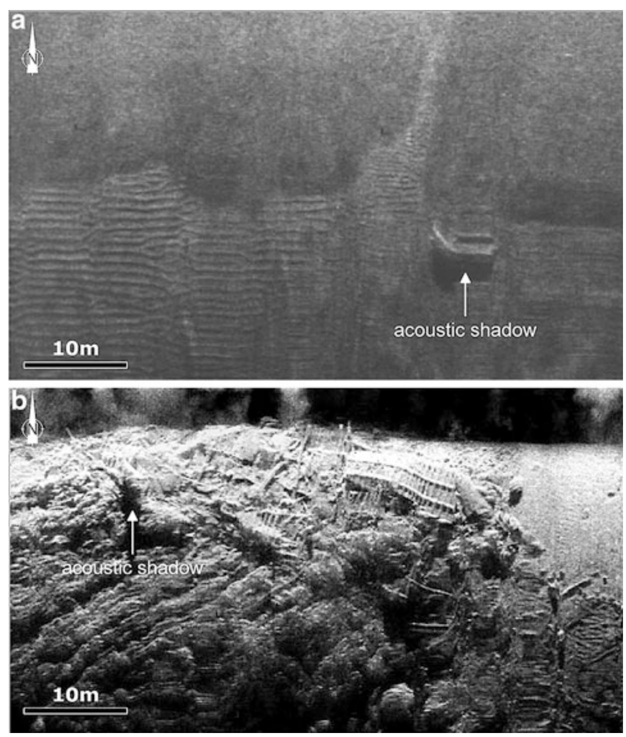


Shipwreck Geoarchaeology, Figure 1 Chirp sub-bottom profile (SBP) acquired over the mid-ship section of the *Invincible* wreck of 1758, the Solent, United Kingdom. These data were acquired with a GeoAcoustics GeoChirp profiler using a 2–8 kHz swept frequency source (Quinn et al., 1998) pulsing at 4 Hz. The Chirp profile over the mid-ship section images the buried oak wreck structure as a high-amplitude reflector with a measured reflection coefficient of −0.27.

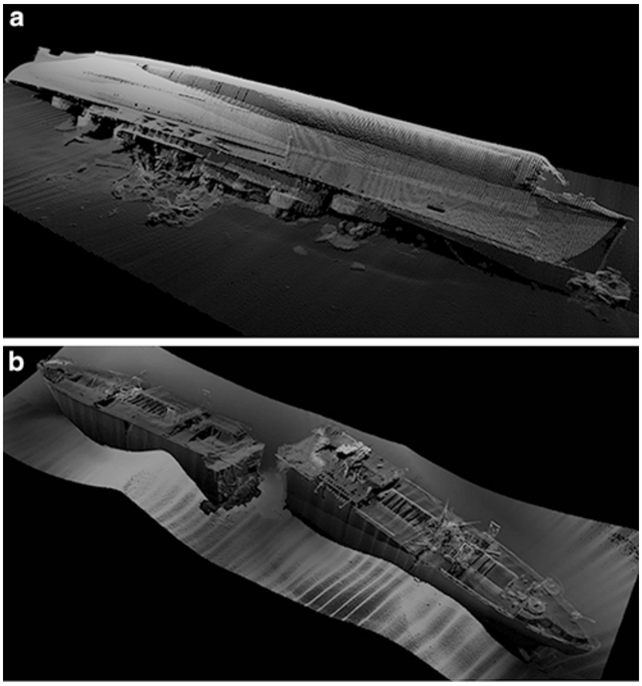
reflect off sedimentary layers in the subsurface. SBP therefore allows archaeologists to detect artifacts and intact wreck structures buried in the upper tens of meters of sediment. At each interface, some of the incident energy is reflected back to the surface, and the remainder is transmitted to deeper layers. For wreck investigations, "Chirp" frequency-modulated SBP (Figure 1) offers the highest resolution solution for imaging buried structures (Plets et al., 2009). The majority of Chirp SBP work is in the frequency range 2–15 kHz, with centimetric vertical resolution theoretically possible. A central frequency of 3.5 kHz is commonly used as a compromise between penetration and resolution.

Side-scan sonar (SSS), traditionally the "workhorse" of marine survey, is a swath sonar technique that provides acoustic images of the seabed generated by two side-looking transceivers mounted on a towfish. The SSS insonifies a corridor of the seafloor underneath the towfish using a highly directed source. SSS relies on backscattered energy and allows users to differentiate material types by measuring the amount of energy returned from each portion of the seafloor. Coarse-grained material scatters the most energy, and fine-grained material scatters the least. SSS systems typically operate as dual-frequency systems, with 100 and 500 kHz sources common (Figure 2). 100 kHz sources are often used for reconnaissance-scale low-resolution wide-area surveys, and 500 kHz sources for detailed high-resolution site-specific surveys.

Multi-beam echo-sounders (MBES), the most effective of the contemporary acoustic mapping systems, are a direct extension of the SBES. Instead of transmitting



Shipwreck Geoarchaeology, Figure 2 Side-scan sonar data from the (**a**) *Appin* (1913) and (**b**) *Oregon* (1945) wreck sites in Belfast Lough (Ireland), acquired using an EdgeTech 272-TD side-scan system operating at 500 kHz with a swath width of 150 m (Quinn et al., 2000).



Shipwreck Geoarchaeology, Figure 3 Multi-beam echo-sounder data of the (**a**) HMS *Royal Oak* and (**b**) SS *Richard Montgomery* wreck sites collected using a Reson 8125 operating at 455 kHz. MBES data were acquired by ADUS DeepOcean for the UK Ministry of Defence.

a single beam vertically downwards, the MBES transmits and receives a fan of narrow beams perpendicular to the ship's axis, producing high-density high-resolution bathymetric data across a swath beneath the survey vessel (Figure 3). Two types of swath systems are commonly employed: true multi-beam echo-sounders and interferometric sonars (also termed bathymetric side-scan sonar). Each of these systems has its merits. In simple terms, MBES systems offer higher-resolution bathymetric data with low-order backscatter data as a by-product, whereas interferometric systems offer lower-order bathymetric data and true side scan. Contemporary MBES can simultaneously acquire depth and backscatter data for each point insonified on the seafloor. These data can be used to derive charts of the seafloor showing relief and backscatter intensity, which can in turn be used to produce geological maps when ground-truthed using direct (grabs, cores) or indirect (video, stills) sampling methods (see below). Despite their complexity and relative expense, MBES now dominate seafloor mapping. MBES have many uses and are designed to operate in various water depths (Lurton, 2010). Deepwater systems are designed for regional survey and operate in the frequency range of 12 kHz (deep ocean mapping) to 30 kHz (continental shelf investigations). The large size and weight of these MBES transceivers limits their installation to deep-sea vessels. Shallow-water systems typically operate at 100–200 kHz and are designed for hydrographic survey of the continental shelves. High-definition systems, operating between 300 and 500 kHz, are used for high-definition work and object detection (Lurton, 2010) that is ideally suited to shipwreck archaeology. Their small size and weight makes them ideal for small-vessel deployment and for mounting on remotely operated underwater vehicles or ROVs.

Non-acoustic prospection methods

Although acoustic methods are by far the most powerful techniques to locate and characterize submerged archaeological sites, magnetic and laser techniques have also proven successful in locating shipwrecks (Gearhart, 2011), and they are therefore sometimes used in combination with acoustic technology. Magnetometers are passive devices that record perturbations in the Earth's magnetic field. They are therefore effective in locating buried shipwrecks containing substantial ferromagnetic components (Gearhart, 2011). Marine magnetometers use either a single sensor to measure the total magnetic field strength or multiple sensors to measure the gradient of the magnetic field. Gradiometers are preferred for archaeology as they are most sensitive to small perturbations in the magnetic field. Proton precession magnetometers have largely been superseded by more sensitive fluxgate and cesium instruments. Differentiating shipwrecks from other magnetic debris can be difficult, especially in busy ports and harbors where magnetic debris is common.

LiDAR (an acronym for Light Detection And Ranging) is an electromagnetic technique used for high-resolution topographic mapping from aircraft. Lasers used in airborne survey are generally in the near-infrared band of the electromagnetic spectrum, between 532 and 1,064 nm. They operate in a similar manner to acoustic devices, transmitting light pulses and recording the time taken for the pulse to travel out, reflect, and travel back to the sensor. The two-way travel time is then multiplied by the speed of light in air and divided by two. When the position and incident angle of the laser scanner is established, the real-world coordinates of the reflecting object can be calculated. Bathymetric LiDAR, recently proven effective in imaging submerged shipwrecks in shallow water (Tian-Yuan Shih et al., 2014), transmits laser pulses at two wavelengths, 532 nm (green) and 1,064 nm (infrared). The green pulse penetrates the water surface and reflects off the seabed, and the red pulse is reflected directly from the sea surface.

Other non-acoustic techniques that have proven successful in imaging submerged shipwrecks are real aperture radar (RAR) K_a band imaging (Hennings and Herbers, 2010) and marine electrical resistivity tomography (Passaro, 2010).

Shipwreck site characterization

Archaeological interpretation of marine geophysical data concentrates on the identification of anomalies, i.e., on appreciable differences between a constant or smoothly varying background and a very strong or "anomalous" geophysical signature. Geophysical anomalies take many forms. For example, a concentration of iron cannon in gullies on a bedrock substrate would give rise to a sharp magnetic anomaly, but may be difficult to interpret from acoustic data. Conversely, a wooden vessel on a planar sand substrate may present an obvious backscatter anomaly, but might be difficult to detect in a magnetometer survey. In reconnaissance surveys, many anomalies are often identified, especially in an area of busy shipping. Larger objects, such as intact shipwrecks, are easy to identify. Smaller objects are often difficult to interpret. Also, some large objects produce relatively small anomalies if a large portion of the structure is buried. Therefore, it helps to have a basis for assigning probability levels to targets. Natural targets tend to possess irregular shapes. Conversely, anthropogenic objects are often regular or angular. Caution is advised, as often man-made objects can be buried (or semi-buried), and therefore the associated anomaly may be masked by sediment. The context of an anomaly is also important. Anomalies sometimes seem out of place in context with the surrounding seafloor. For example, a small angular anomaly on a planar sand seafloor may be deemed of higher interest than a small angular anomaly on a rock-strewn platform. Experience becomes a valuable asset here, as does luck, and it is often advisable to survey a target from different directions. All of these factors highlight the need to develop objective means for classifying and identifying archaeological anomalies in geophysical data.

Geophysical characterization of shipwreck sites

Although some research has been conducted on the geophysical signatures of archaeological materials submerged and buried in marine environments, it remains a relatively poorly understood subject. In nearshore waters, misinterpretation of archaeo-geophysical data is often compounded by the presence of modern anthropogenic debris; however, attempts to distinguish archaeological objects from natural materials through automated classification and controlled detection have met with some success. Lawrence and Bates (2001) successfully detected wood and metallic wrecks in SBES data using acoustic ground discrimination systems (AGDS). AGDS derive estimates of "roughness" and "hardness" from echosounder data by examining the signal characteristics of primary and multiple reflectors in the data.

Research has also been conducted on imaging buried shipwrecks using high-resolution seismic sources. In normal subsurface geological situations, values of reflection coefficients fall into the range of ± 0.1 (Anstey, 1981), with the majority of energy being transmitted. However, Quinn et al. (1997) demonstrated that reflection coefficient values for wood buried in unconsolidated marine sediments are generally large and negative (between -0.2 and -0.8), indicating that seismic instruments can readily image wooden artifacts and structures submerged and buried in the marine environment. Subsequently Arnott et al. (2005) investigated the impact of wood degradation on seismic signatures and concluded that the actual degradation state of buried archaeological material could also be estimated from acoustic properties. This idea was further explored by Plets et al. (2008, 2009) using Chirp technology, proving that the reflection coefficient of buried wood becomes increasingly negative with increased deterioration of the wood structure.

Experimental work to image and detect archaeological material and objects from geological "noise" in backscatter data has also proven successful (Quinn et al., 2005). A control experiment, where a range of organic and inorganic archaeological material was deliberately submerged and surveyed, proved that a very wide range of archaeological materials can be imaged in geophysical surveys, but that individual archaeological targets can be difficult (or impossible) to resolve when they are imaged out of context (Quinn et al., 2005). Recent advances in the processing of MBES-derived backscatter data (much influenced by advances in seabed sediment and benthic habitat mapping) demonstrate that it is possible to detect shipwrecks from the surrounding seabed using remote classification techniques (Masetti and Calder, 2012). Although this approach is promising, more research is needed to develop robust techniques that will successfully identify shipwreck sites in high-volume, high-density MBES data sets.

Ground truthing and direct sampling of shipwreck sites

Whatever subjective or objective methods are used to interpret geophysical data for archaeological prospection, at a minimum, a representative sample of the geophysical data needs to be ground-truthed. Ground-truthing methods traditionally comprise direct sampling (using surficial sediment samplers or coring devices) or optical imaging of the seafloor. A variety of dredges, corers, and grab sampling tools are used for collecting rock and sediment samples from the seafloor and shallow subsurface, including Day Grabs and Van Veen Grabs. Grab samplers employ two spring-hinged jaws that close when the device impacts the seafloor, with sediment samples retrieved for particle-size and contaminant analyses. Gravity , vibra-, and/or push cores can also be used, notably when deeper sedimentary horizons need to be sampled. Optical ground truthing of geophysical data is traditionally conducted using drop-down video cameras (mounted with still and/or video cameras), towed arrays, ROVs, or divers.

Understanding shipwreck sites

Physical aspects of wreck site formation

Research into processes that form the submerged archaeological record is important, as it informs effective in situ conservation and preservation of archaeological sites. Two general classes of formation processes are recognized: culturally created (C-transforms) and naturally created (N-transforms) (Schiffer, 1987). Marine geoarchaeologists tend to be more concerned with understanding N-transforms – specifically, the linked physical processes operating in the water column (hydrodynamics) and on the seafloor (sediment dynamics).

As shipwrecks are inextricably linked with the surrounding natural environment, site formation processes at wreck sites are dependent upon anthropogenic influence and combined physical, biological, and chemical processes. Physical processes tend to dominate in initial stages of site formation, with biological and chemical influences important in the later stages (Ward et al., 1999a). Iron and wooden wrecks tend to deteriorate differently: iron wrecks succumb to physical and chemical processes, and wooden wrecks are destroyed by combined physical and biological processes (Ward et al., 1999a).

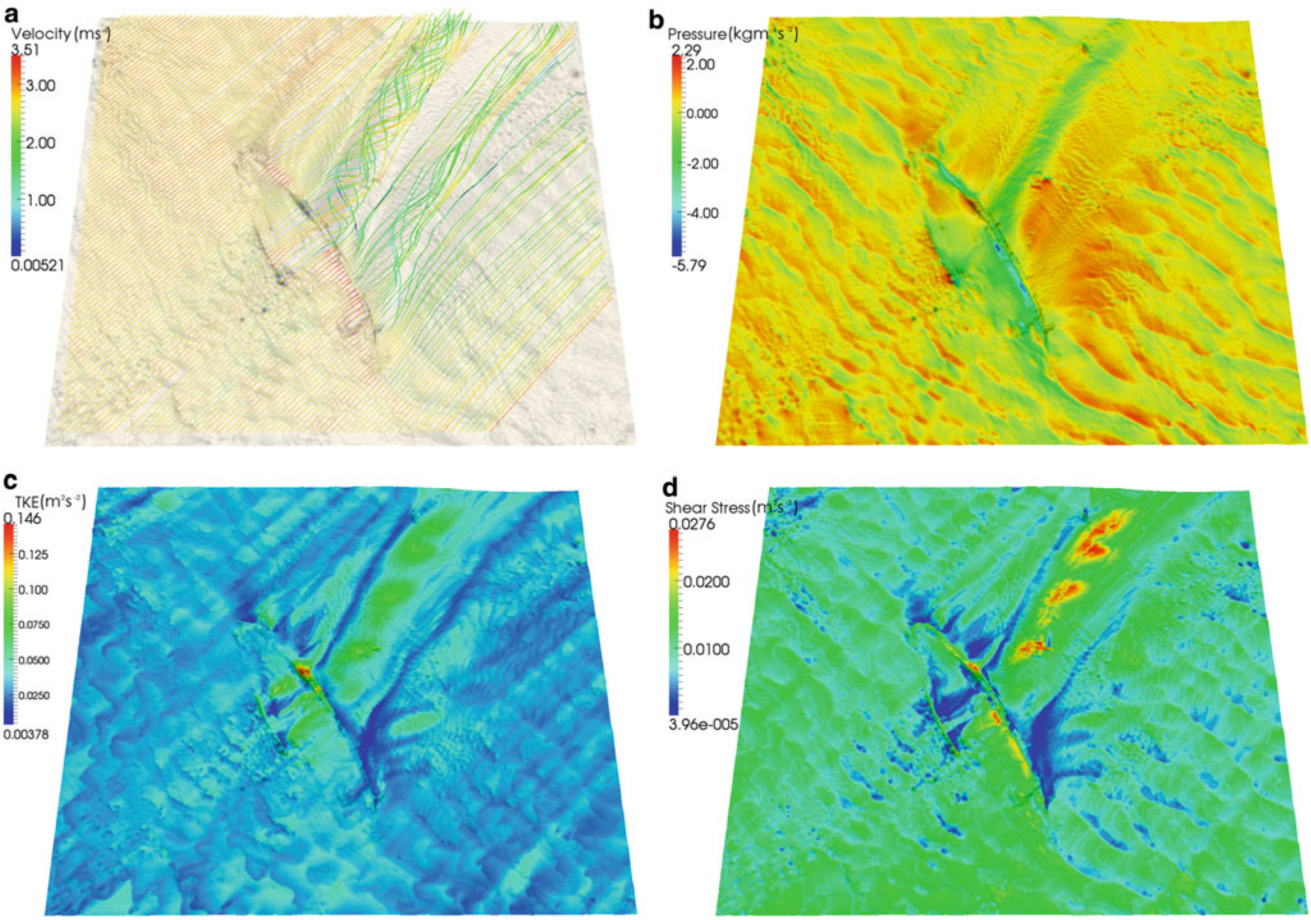
Although many authors describe wrecks as being in some form of equilibrium state with the surrounding environment (Gregory, 1995; Quinn et al., 1997; Ward et al., 1999a), it is important to acknowledge that wreck sites act as open systems, with the exchange of material (sediment, water, organics, and inorganics) and energy (wave, tidal, storm) across system boundaries (Quinn, 2006). Wrecks are therefore in a state of dynamic (not steady state) equilibrium with respect to the natural environment: they are characterized by negative disequilibrium, ultimately leading to wreck disintegration (Quinn, 2006).

Positive and negative feedbacks operate between physical, chemical, and biological processes in the water column, sediment pile, and the wreck as it disintegrates and interacts with the surrounding environment (Ward et al., 1999a; Ward et al., 1999b). Fundamental processes driving site formation are therefore dependent upon the complex erosion (net sediment/material loss) and accretion (net sediment/material deposition) history of wreck sites. In high-energy environments, waves, currents, and sediment abrasion are more significant than chemical or biological processes (Ward et al., 1999a). However, a single shipwreck in a normally low-energy environment may experience high-energy storm events, causing intense periods of structural deterioration and material loss over short durations. Furthermore, exposed parts of wreck structures tend to be affected by aerobic bacteria, wood borers, and increased corrosion rates, while buried wreck components tend to be affected by anaerobic bacteria (Ward et al., 1998). Therefore, even major chemical and biological processes contributing to site formation are constrained by physical process (Quinn, 2006).

The introduction of an object to the seafloor leads to an increase in flow velocity and turbulence (Whitehouse, 1998), causing changes in the flow regime in its immediate environs and resulting in one or a combination of (1) flow contraction, (2) formation of a horseshoe vortex in front of the structure, (3) formation of lee-wake vortices behind the structure (sometimes accompanied by vortex shedding), (4) turbulence, (5) occurrence of reflection and diffraction waves, (6) wave breaking, and (7) sediment liquefaction promoting material loss from the site (Sumer et al., 2001). A horseshoe vortex is formed by the rotation of incoming flow. Under the influence of an adverse pressure gradient produced by the structure, the boundary layer on the bed upflow of the structure undergoes a three-dimensional separation, rolls up to form a swirling vortex around the structure, and trails off downflow (Sumer et al., 1997). The morphology of horseshoe vortices can be strongly distorted, resulting in complicated flow patterns. One such result is vortex shedding, where self-propelling, closed ring structures are formed and transported by flow (Testik et al., 2005). Lee-wake vortices are formed by rotation in the boundary layer over the surface of the object. End effects (from the tips of the structure, in this case the bow and stern of a submerged vessel) play a dominant role in the flow pattern and strongly modify the structure of vortices. Lee-wake vortices emanating from the surface of the wreck are brought together in the vicinity of the structure due to flow convergence. Additionally, two counter-rotating vortices form a vortical region in the near wake on the lee side of the structure (Testik et al., 2005).

These processes act to increase local sediment transport and subsequently lead to scour (Sumer et al., 2001) around wrecks. Scouring subsequently results in the lowering of the seabed from some previously obtained quasi-equilibrium level due to (1) flow velocity increase near the object, (2) resulting increase in the local Shields parameter (a nondimensional number used to calculate the initiation of motion of sediment in a fluid flow), and (3) subsequent divergences in the sediment transport regime (Voropayev et al., 2003). When scour occurs on fine-grained (silt or clay) seabeds, the eroded material is carried away from the wreck site in suspension, leaving a seafloor depression that may not be readily infilled by natural processes (Whitehouse et al., 2011). Where scouring takes place in coarse-grained deposits (sand or gravel), it usually results in local deposition (often comprising the eroded material) in addition to scour. Scouring ultimately leads to wreck site instability and material loss.

Seabed scour operates on a variety of temporal scales, with scouring at static structures initially occurring rapidly (over a period of days to weeks) but approaching ultimate (equilibrium) values asymptotically (Whitehouse, 1998). Due to the dynamic and mobile nature of submerged wreck sites and artifact scatters in the nearshore zone, the process of scouring can occur at a wide range of temporal scales (hours to decades) as sites and objects are invariably covered and uncovered due to external forcing. Furthermore, the total or partial mobility of wreck structures and associated artifacts can lead to archaeological objects acting as mobile nuclei for scour initiation, further



Shipwreck Geoarchaeology, Figure 4 Output from CFD model over a bathymetric surface derived from an MBES shipwreck survey: (**a**) three-dimensional flow velocity, (**b**) pressure map, (**c**) turbulent kinetic energy map, and (**d**) shear stress map of the seafloor.

complicating scour processes (McNinch et al., 2006; Quinn, 2006).

Seabed scour also operates on a variety of spatial scales, from complete wreck sites to individual objects or artifacts. Controls on the spatial extent of scouring at wreck sites include a combination of the orientation, shape, and size of the causative object; the seafloor and subsurface geology; the water depth; and the prevailing hydro- and sediment dynamics (Caston, 1979; Quinn, 2006). Time-lapse MBES surveys have proven effective in quantifying morphological change at wreck sites due to anthropogenic and natural forcing (Quinn and Boland, 2010), with resultant data useful in the development of site formation models.

Mathematical modeling of shipwreck sites

Experimental studies attempting to characterize the hydro- and sediment dynamics at submerged shipwreck sites have traditionally relied on laboratory-based physical models (e.g., Saunders, 2005) or field instrumentation deployments (e.g., Dix et al., 2007). However, lab-based flume experiments using scaled models, although useful in the attempt to replicate the natural environment, are usually limited by scaling factors. Field-based experiments, using high-resolution acoustic Doppler current profiler (ADCP) deployments, are expensive and logistically difficult.

Recently, researchers have investigated mathematical modeling as a relatively inexpensive and adaptable method to characterize hydrodynamic flows around wrecks. Using computational fluid dynamics (CFD), MBES data from a shipwreck site and boundary conditions constrained by field measurements (sediment samples and flow measurements) Smyth and Quinn (2014) successfully simulated the three-dimensional flow velocity field around a fully submerged shipwreck (Figure 4). They demonstrate that the presence of a shipwreck on the seafloor leads to an increase in flow velocity and turbulence, causing changes in the flow regime in its immediate environs. Flow contraction, formation of lee-wake vortices behind the structure (accompanied by vortex shedding), and turbulence were all simulated and quantified in this study. The secondary products derived from the CFD modeling confirm that flow velocity and turbulence are both amplified by the presence of a wreck, causing changes in the morphology of the flow regime. Shear stress and turbulent kinetic energy (TKE) amplification three to four times greater than ambient values were recorded downstream of the wreck structure in the model environment.

The results presented in this CFD study indicate that the secondary products derived from the modeling are crucial in understanding the areas and components of wreck sites most at risk by natural forcing, and therefore those elements should be prioritized when it comes to in situ conservation (Smyth and Quinn, 2014). For example, areas of wreck sites identified as experiencing elevated or amplified TKE, pressure, and/or shear stress are most under threat from mechanical stress and therefore might be targeted in the early stages of preservation and in situ conservation. Related to this, after protecting a site (using additional sediment, sandbags, or geotextiles, see for example Manders et al., 2008), it is suggested that a repeat MBES survey could be conducted and a new CFD model run to test the effectiveness of conservation measures (Smyth and Quinn, 2014).

Summary

Acoustic surveys are now an essential part of shipwreck investigations in (1) locating wrecks, (2) characterizing wreck sites, and (3) modeling the hydrodynamics and sediment dynamics of these sites. Each of these phases of investigation has benefited enormously from technological and methodological advances in acoustic imaging, digital rendering, and numerical modeling over the past two decades, and they will continue to do so into the future.

Bibliography

Anstey, N. A., 1981. *Signal Characteristics and Instrument Specifications*, 2nd edn. Berlin: Gebrüder Borntraeger.

Arnott, S. H. L., Dix, J. K., Best, A. I., and Gregory, D. J., 2005. Imaging of buried archaeological materials: the reflection properties of archaeological wood. *Marine Geophysical Researches*, **26**(2–4), 135–144.

Bull, J. M., Quinn, R., and Dix, J. K., 1998. Reflection coefficient calculation from marine high resolution seismic reflection (Chirp) data and application to an archaeological case study. *Marine Geophysical Researches*, **20**(1), 1–11.

Caston, G. F., 1979. Wreck marks: indicators of net sand transport. *Marine Geology*, **33**(3–4), 193–204.

Dix, J. K., Lambkin, D. O., Thomas, M. D., and Cazenave, P. W., 2007. *Modelling exclusion zones for marine aggregate dredging*. English Heritage Aggregate Levy Sustainability Fund Project 3365 Final Report (www.ads.adhs.ac.uk). Southampton: School of Ocean and Earth Science, Southampton University.

Gearhart, R., 2011. Archaeological interpretation of marine magnetic data. In Catsambis, A., Ford, B., and Hamilton, D. L. (eds.), *The Oxford Handbook of Maritime Archaeology*. Oxford: Oxford University Press, pp. 90–113.

Gregory, D., 1995. Experiments into the deterioration characteristics of materials on the Duart Point wreck site: an interim report. *International Journal of Nautical Archaeology*, **24**(1), 61–65.

Hennings, I., and Herbers, D., 2010. A theory of the K_a band radar imaging mechanism of a submerged wreck and associated bed forms in the southern North Sea. *Journal of Geophysical Research: Oceans*, **115**(C10), C10047.

Lawrence, M. J., and Bates, C. R., 2001. Acoustic ground discrimination techniques for submerged archaeological site investigations. *Marine Technology Society Journal*, **35**(4), 65–73.

Lurton, X., 2010. *An Introduction to Underwater Acoustics: Principles and Applications*, 2nd edn. Heidelberg: Springer.

Manders, M., Gregory, D. J., and Richards, V., 2008. The *in situ* preservation of archaeological sites underwater: an evaluation of some techniques. In May, E., Jones, M., and Mitchell, J. (eds.), *Heritage, Microbiology and Science: Microbes, Monuments and Maritime Materials*. Cambridge: RSC Publishing. Royal Society of Chemistry (Great Britain), Special Publication, Vol. 315, pp. 179–203.

Masetti, G., and Calder, B. R., 2012. Remote identification of a shipwreck site from MBES backscatter. *Journal of Environmental Management*, **111**, 44–52.

McNinch, J. E., Wells, J. T., and Trembanis, A. C., 2006. Predicting the fate of artefacts in energetic, shallow marine environments: an approach to site management. *International Journal of Nautical Archaeology*, **35**(2), 290–309.

Passaro, S., 2010. Marine electrical resistivity tomography for shipwreck detection in very shallow water: a case study from Agropoli (Salerno, southern Italy). *Journal of Archaeological Science*, **37**(8), 1989–1998.

Plets, R., 2013. Underwater survey and acoustic detection and characterization of archaeological materials. In Menotti, F., and O'Sullivan, A. (eds.), *The Oxford Handbook of Wetland Archaeology*. Oxford: Oxford University Press, pp. 433–449.

Plets, R. M. K., Dix, J. K., and Best, A. I., 2008. Mapping of the buried Yarmouth Roads wreck, Isle of Wight, UK, using a Chirp sub-bottom profiler. *International Journal of Nautical Archaeology*, **37**(2), 360–373.

Plets, R. M. K., Dix, J. K., Adams, J. R., Bull, J. M., Henstock, T. J., Gutowski, M., and Best, A. I., 2009. The use of a high-resolution 3D Chirp sub-bottom profiler for the reconstruction of the shallow water archaeological site of the Grace Dieu (1439), River Hamble, UK. *Journal of Archaeological Science*, **36**(2), 408–418.

Plets, R., Quinn, R., Forsythe, W., Westley, K., Bell, T., Benetti, S., McGrath, F., and Robinson, R., 2011. Using multibeam echo-sounder data to identify shipwreck sites: archaeological assessment of the Joint Irish Bathymetric Survey data. *International Journal of Nautical Archaeology*, **40**(1), 87–98.

Quinn, R., 2006. The role of scour in shipwreck site formation processes and the preservation of wreck-associated scour signatures in the sedimentary record – evidence from seabed and sub-surface data. *Journal of Archaeological Science*, **33**(10), 1419–1432.

Quinn, R., 2011. Acoustic remote sensing in maritime archaeology. In Catsambis, A., Ford, B., and Hamilton, D. L. (eds.), *The Oxford Handbook of Maritime Archaeology*. Oxford: Oxford University Press, pp. 68–89.

Quinn, R., and Boland, D., 2010. The role of time-lapse bathymetric surveys in assessing morphological change at shipwreck sites. *Journal of Archaeological Science*, **37**(11), 2938–2946.

Quinn, R., Bull, J. M., and Dix, J. K., 1997. Imaging wooden artefacts using Chirp sources. *Archaeological Prospection*, **4**(1), 25–35.

Quinn, R., Adams, J. R., Dix, J. K., and Bull, J. M., 1998. The Invincible (1758) site – an integrated geophysical assessment. *International Journal of Nautical Archaeology*, **27**(2), 126–138.
Quinn, R., Cooper, A. J. A. G., and Williams, B., 2000. Marine geophysical investigation of the inshore coastal waters of Northern Ireland. *International Journal of Nautical Archaeology*, **29**(2), 294–298.
Quinn, R., Dean, M., Lawrence, M., Liscoe, S., and Boland, D., 2005. Backscatter responses and resolution considerations in archaeological side-scan sonar surveys: a control experiment. *Journal of Archaeological Science*, **32**(8), 1252–1264.
Saunders, R. D., 2005. *Seabed Scour Emanating from Submerged Three Dimensional Objects: Archaeological Case Studies*. Unpublished PhD thesis, University of Southampton.
Schiffer, M. B., 1987. *Formation Processes of the Archaeological Record*. Albuquerque: University of New Mexico Press.
Smyth, T. A. G., and Quinn, R., 2014. The role of computational fluid dynamics in understanding shipwreck site formation processes. *Journal of Archaeological Science*, **45**, 220–225.
Sumer, B. M., Christiansen, N., and Fredsøe, J., 1997. The horseshoe vortex and vortex shedding around a vertical wall-mounted cylinder exposed to waves. *Journal of Fluid Mechanics*, **332**, 41–70.
Sumer, B. M., Whitehouse, R. J. H., and Tørum, A., 2001. Scour around coastal structures: a summary of recent research. *Coastal Engineering*, **44**(2), 153–190.
Testik, F. Y., Voropayev, S. I., and Fernando, H. J. S., 2005. Flow around a short horizontal bottom cylinder under steady and oscillatory flows. *Physics of Fluids*, **17**(4), 47–103.
Tian-Yuan Shih, P., Chen, Y.-H., and Chen, J.-C., 2014. Historic shipwreck study in Dongsha Atoll with bathymetric LiDAR. *Archaeological Prospection*, **21**(2), 139–146.
Voropayev, S. I., Testik, F. Y., Fernando, H. J. S., and Boyer, D. L., 2003. Burial and scour around short cylinder under progressive shoaling waves. *Ocean Engineering*, **30**(13), 1647–1667.
Ward, I. A. K., Larcombe, P., and Veth, P., 1998. Towards new process-orientated models for describing wreck disintegration – an example using the Pandora wreck. *Bulletin of the Australian Institute for Maritime Archaeology*, **22**, 109–114.
Ward, I. A. K., Larcombe, P., and Veth, P., 1999a. A new process-based model for wreck site formation. *Journal of Archaeological Science*, **26**(5), 561–570.
Ward, I. A. K., Larcombe, P., Brinkman, R., and Carter, R. M., 1999b. Sedimentary processes and the *Pandora* wreck, Great Barrier Reef, Australia. *Journal of Field Archaeology*, **26**(1), 41–53.
Westley, K., Quinn, R., Forsythe, W., Plets, R., Bell, T., Benetti, S., McGrath, F., and Robinson, R., 2011. Mapping submerged landscapes using multibeam bathymetric data: a case study from the north coast of Ireland. *International Journal of Nautical Archaeology*, **40**(1), 99–112.
Whitehouse, R., 1998. *Scour at Marine Structures: A Manual for Practical Applications*. London: Thomas Telford.
Whitehouse, R. J. S., Sutherland, J., and Harris, J. M., 2011. Evaluating scour at marine gravity structures. *Maritime Engineering*, **164**(MA4), 143–157.

Cross-references

Coastal Settings
Geomorphology
Geographical Information Systems (GIS)
Remote Sensing in Archaeology
Site Formation Processes
Submerged Continental Shelf Prehistory

SITE FORMATION PROCESSES

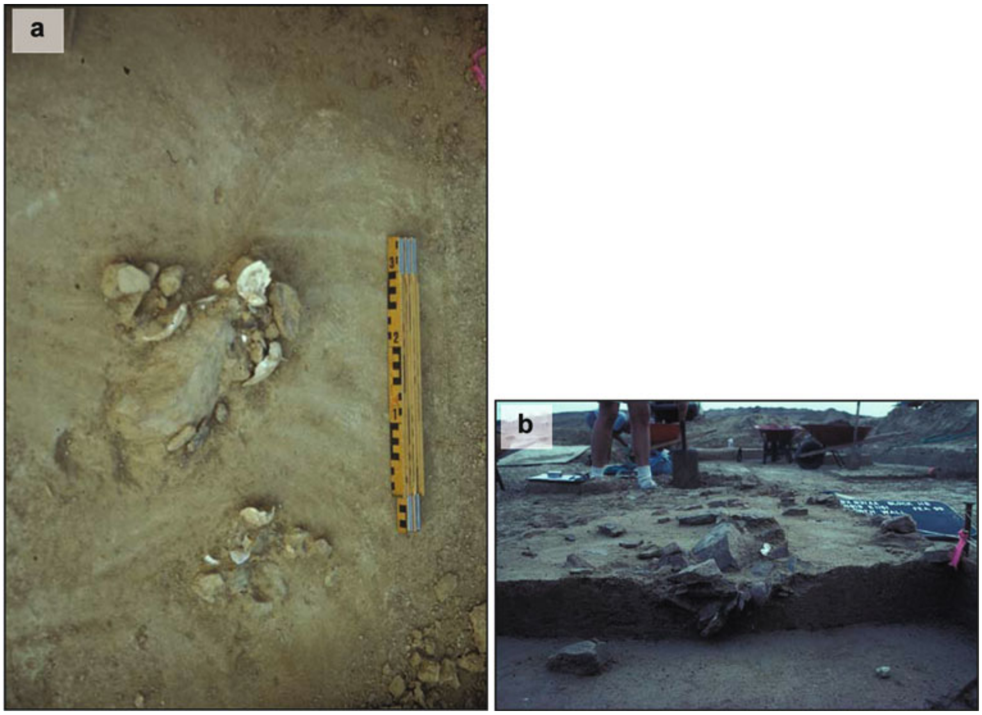
Rolfe D. Mandel[1], Paul Goldberg[2] and Vance T. Holliday[3]
[1]Department of Anthropology, University of Kansas, Lawrence, KS, USA
[2]Department of Archaeology, Emeritus at Boston University, Boston, MA, USA
[3]Anthropology and Departments Geosciences, University of Arizona, Tucson, AZ, USA

Introduction

Site formation processes are "the factors that create the historic and archaeological records" (Schiffer, 1987, 7). These factors include both natural and anthropogenic forces operating in different depositional environments and contributing to postdepositional disturbances. Formation processes affect the spatial integrity of both artifacts and sites, and they affect cultural deposits in different ways depending on the site's age, geomorphic setting, sediments and soils, climate, and type and the complexity of occupation (Goldberg and Macphail, 2006). Schiffer (1972, 1987) stressed that the reconstruction of human behavior must be inferred from the archaeological context, which he defined as the three-dimensional spatial patterning of individual artifacts, features, and other debris on a site. However, before archaeologists can reach meaningful conclusions about human behavior from the archaeological context, they must know how it was created (Waters, 1992, 11).

According to Schiffer (1987), two processes create a site and its associated context: cultural transformations and natural transformations. Cultural, or anthropogenic, transformations are products of human activities that create the patterns of artifacts and features at a site. Cultural deposits are not emplaced in static environments, however, and natural transformations involving physical, chemical, and biological processes eventually affect the context of the material remains at a site. Geoarchaeologists are concerned with both natural and cultural site formation processes and how these shape the context of a site and the archaeological record.

It is likely that geoarchaeologists were aware of the notion of "site formation processes" long before the term became widely known through the publication of Schiffer's 1987 volume, *Formation Processes of the Archaeological Record*. In the early and mid-twentieth century, both European and North American geoarchaeologists whose research background was in the geosciences investigated Quaternary environments and intrinsically thought about how the archaeological sites they studied were formed, even if they didn't specifically articulate this concept at the time (e.g., Sellards, 1917, 1938; Bryan and Ray, 1940; Zeuner, 1946; Cornwall, 1953; Bordes, 1954; Bonifay, 1956; Laville, 1964; Haynes and Agogino, 1966). By the beginning of the



Site Formation Processes, Figure 1 As floodwaters moved across a former surface soil (now deeply buried) representing the early Holocene floodplain of the Medina River at the Richard Beene site in south central Texas, cultural deposits were modified by the flowing water. (**a**) Photograph of two amorphous Early Archaic (ca. 8800–8600 BP) artifact concentrations showing fire-cracked rock (*FCR*), mussel shells, and chipped stone, some showing a vertical angle of repose. (**b**) Photograph of a cross-sectioned Early Archaic FCR feature. Note the imbricated FCR (From Thoms (2007)).

1980s, a more formal awareness and treatment of the subject of how archaeological sites form was presented by Karl W. Butzer (1982), who articulated the interaction between natural and cultural elements that shape the appearance of a site. Although it is an important topic in archaeology, site formation processes were regarded by Butzer to be the primary task of geoarchaeology. Nevertheless, considering the number of archaeological sites excavated throughout the world, it is remarkable that so few studies of sites included geoarchaeological investigations addressing formation and postdepositional processes.

In evaluating site formation processes, it is useful to consider some logical categories. There are two major types of sites: open-air sites and those in caves and rock-shelters. (For sites involving mostly human agencies in their formation (historic, urban, etc.), see the entries on "Built Environment" in this volume.) In addition, such processes can be operationally broken down into three temporal ranges: those that took place before, during, and/or after occupation. As a whole, these processes may include natural and cultural sedimentation and modifications (e.g., trampling, discarding sweepings), soil formation (pedogenesis), and diagenesis.

Open-air sites

The major depositional systems associated with open-air sites are alluvial (flowing water), eolian (wind), lakes and basins, glacial, and coastal marine. These depositional systems have sedimentary contexts that are addressed here in terms of their role in site formation processes.

Alluvial systems

In the past, humans have been attracted to streams, often living on floodplains, terraces, or alluvial fans and exploiting the abundant resources available in alluvial settings. Although alluvial landscapes are conducive to the initial accumulation of artifacts, fluvial processes may restructure the artifact patterns (Rapp and Hill, 2006, 75). For example, where sites are situated on or near the banks of stream channels, high-energy floods tend to modify cultural deposits dramatically by displacing artifacts vertically and horizontally. At the Richard Beene site in south central Texas (Figure 1), Early Archaic features consisting mostly of large pieces of fire-cracked rock with smaller or lighter items, including chert flakes, mussel shells, and pebbles, were recorded in small scour holes on the surface of a deeply buried paleosol representing an early Holocene floodplain surface (Thoms, 2007, 79).

Many of the flakes and mussel shells, along with tabular pieces of fire-cracked rock, occurred in a near-vertical angle of repose and were imbricated. It is likely that one or more flood-scouring events on this floodplain in the early Holocene removed the fine-grained matrix from burnt-rock features, such that the large clasts remained essentially in place horizontally but were displaced vertically and served as traps for smaller objects being transported laterally by floodwaters moving across the former floodplain.

In some cases, stream erosion may completely remove artifacts, cultural features, and even parts of sites, thereby destroying evidence of human occupation. On the other hand, alluviation (deposition of sediment by streams) can result in rapid burial and preservation of cultural deposits. Because the material remains of human occupation in stream valleys have passed through a geologic filter (i.e., erosion, deposition, and landscape stability) to become the archaeological record, understanding the nature of the temporal and spatial patterns that this filter has imposed on the archaeological record throughout a drainage network is the first task in identifying archaeological patterns that reflect human choices (Bettis and Mandel, 2002a; Mandel, 2006). For example, in a systematic study of drainage basins in the Central Plains of the USA, Mandel (1995) determined that the paucity of recorded Archaic sites, especially those dating between ca. 8000 and 4000 BP, is a result of fluvial erosion or sedimentation and not due to any peculiarities of the prehistoric settlement patterns. Those processes have affected the archaeological record by either removing or burying sites.

Artifact taphonomy can be complex in alluvial settings, and it cannot be assumed that cultural materials were initially deposited in the very sediments from which they were recovered (Rapp and Hill, 2006, 76). Artifacts are often incorporated into the sediments by channel migration and thereby redeposited within the alluvium; in some cases, the artifacts have gone through multiple cycles of redeposition. In a study of Paleolithic cultural materials recovered from deposits of gravel-rich alluvium in the lower Thames River valley, Gibbard (1994) determined that most of the artifacts were in secondary contexts. Such artifacts were sorted, smoothed, and rounded, indicating that they were rolled over great distances by water. In the same deposits, accumulations of unsorted and unabraded artifacts also were recorded, indicating that some of the artifacts were transported minimally if at all by flowing water of low energy.

Schick (1987) and Petraglia and Nash (1987) conducted experiments designed to identify how fluvial processes affected bone and stone artifacts. Their experiments and conclusions were similar. Both groups experientially tested movement and burial of lithic artifacts using test plots in different settings. In their experiments, smaller items were more likely to be transported by water, while larger or heavier items (>15 g in one experiment, cores in the other) tended to remain in situ despite strong flow events. According to Petraglia and Nash (1987, 126), "the integrity of sites located in fluvial contexts is related to the tempo, magnitude and duration of hydrological events." By studying the new "sites" created by redeposited cultural materials, Schick (1987) and Petraglia and Nash (1987) were able to demonstrate that artifacts may be redeposited in multiple locations, they may be sorted by size, and lighter items may be carried farther downstream. When the original site areas and the areas of redeposited artifacts were compared, the researchers discovered that the zones of redeposited artifacts were elongated in the direction of the water flow (Schick, 1987). Petraglia and Nash (1987) recorded the number of artifacts that were buried during the course of the experiment and determined that once the artifacts were buried, they were more likely to remain in place.

Eolian systems

As with water, both depositional and erosional processes are associated with wind, which can both cover and preserve cultural deposits or cause disturbances and exhume an archaeological site. There are two general types of eolian deposits: those consisting of silty sediment, or loess, and those consisting of sand. Loess is widespread in China, Central Asia, Ukraine, Central and Western Europe, Argentina, and the Great Plains and Midwest of North America. Sandy eolian deposits comprise dunes, sand sheets, and sand seas and occur mostly in arid and semiarid environments throughout the world.

Although wind can bury artifacts and cultural features in loess or sand deposits and thus preserve them within a stratified context, eolian processes often cause major transformations of the archaeological record at sites. In particular, where stratified sequences of artifact-bearing eolian sands exist initially, wind erosion can remove sediment, a process referred to as deflation, thereby causing the collapse of the sequences and the mixing of archaeological components (Rapp and Hill, 2006, 65). For example, on sand sheets and sand seas in the Western Desert of Egypt, deflation has created lag deposits consisting of artifacts from different cultural periods (Schild and Wendorf, 1975; Wendorf and Schild, 1980; Mandel and Simmons, 2001). Deflation therefore removes fine sediments causing a reduction in ground level and the formation of denser scatters of the larger particulate matter and artifacts that the wind was not strong enough to move. Wood and Johnson (1978, 359) describe deflation as when "nature had done the excavating and, unfortunately, had left a two-dimensional chronologically blurred site context for archaeologists."

In addition to affecting the vertical integrity of cultural deposits through deflation, wind can cause modification and destruction of artifacts through abrasion. Also, small artifacts, such as micro-debitage, may be redeposited by the wind.

Sand dunes are dynamic geomorphic features, often shifting through time and experiencing episodes of deflation. As a consequence, the context of cultural deposits on or within dunes is prone to severe modification. At the Krmpotich site in the Killpecker Dunes of southwestern Wyoming, it is likely that the assemblage of Folsom artifacts was incorporated into a lag deposit resulting from at least one episode of deflation sometime during the Holocene (Mayer, 2002). Subsequent reactivation of the dunes brought about the burial of the Folsom assemblage.

Experimental studies have been conducted to determine the effects of wind on the distribution of artifacts, especially in sandy sediments (e.g., Bowers et al., 1983; Shelley and Nials, 1983; Simms, 1984; Wandsnider, 1988). Through a series of experiments, Wandsnider (1988) determined that wind can move small artifacts directly or transport items indirectly by forming small obstruction dunes behind the artifact, which then "plow the artifacts along." Also, the wind may excavate small pits behind and beneath larger artifacts into which they may roll. Despite these effects of wind, Wandsnider (1988) argued that it is unlikely such disturbance would impact the artifact distribution to an extent that the spatial integrity of the behavior that created it is compromised.

Cameron et al. (1990) determined that the size of artifacts strongly influences their movement by wind. Whereas small artifacts (<8 mm) tend to move great distances downwind even if this movement involves traveling upslope, larger ones generally are not moved very far if at all by wind. Also, artifacts tend to settle into sandy sediments during the first few months after they are deposited; there, they become partially buried, making them less likely to be moved by wind or water (Petraglia and Nash, 1987; Schick, 1987; Wandsnider, 1988).

Lakes and basins

Archaeological sites are common on the margins of lakes and basins because of the presence of water, either permanent or intermittent, and abundant and diverse food resources that attracted humans. Whereas lakes are large inland bodies of standing water, i.e., larger than ponds, basins are highly variable in size, with surface areas ranging from thousands of square kilometers to a few tens of square meters. Examples of small basins include kettles (also called potholes, formed by the melting of glacial ice blocks that calved off of retreating ice sheets), pans, and some playas created by deflation.

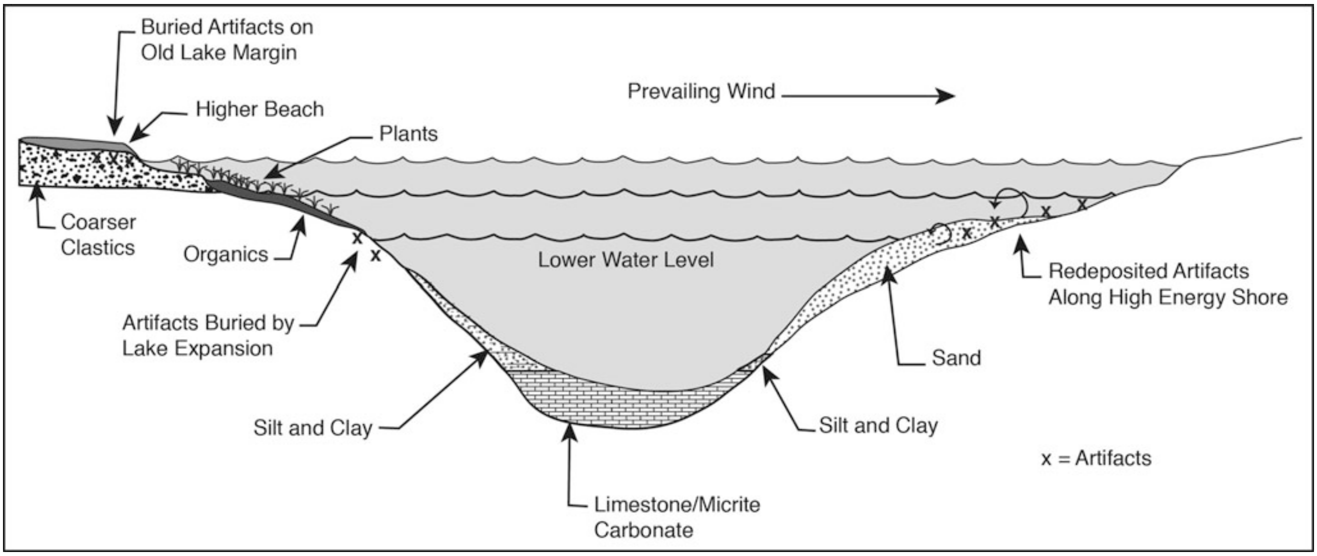
The margins of lakes and basins are diverse and dynamic transitional environments located between terrestrial and aquatic ecosystems. Here, small fluctuations in environmental parameters are often recorded by shifts in sedimentary pattern (Feibel, 2001, 127). These shifts can be especially dramatic when water levels rise and fall, causing facies changes that alternate between subaerial and subaqueous depositional settings. The vertical and horizontal sequence of sediments along the margins of a lake or basin records details of the depositional environment as well as the events that led to burial and preservation of archaeological assemblages (Feibel, 2001, 127).

As a transitional environment, a lake or basin margin is characterized by a complex pattern of sedimentation and sediment modification. Feibel (2001, 134) identified three types of transitions associated with lake margins: (1) the successive shifting of ambient erosional, transport, and depositional processes; (2) the geologically abrupt and often catastrophic effect of large-scale events, such as strong storms that generate waves; and (3) the often subtle but significant switch from subaqueous to subaerial conditions as water levels rise and fall. Also, the effect of time may cause postdepositional modification, including dissolution, cementation, and soil formation, all of which can affect archaeological deposits.

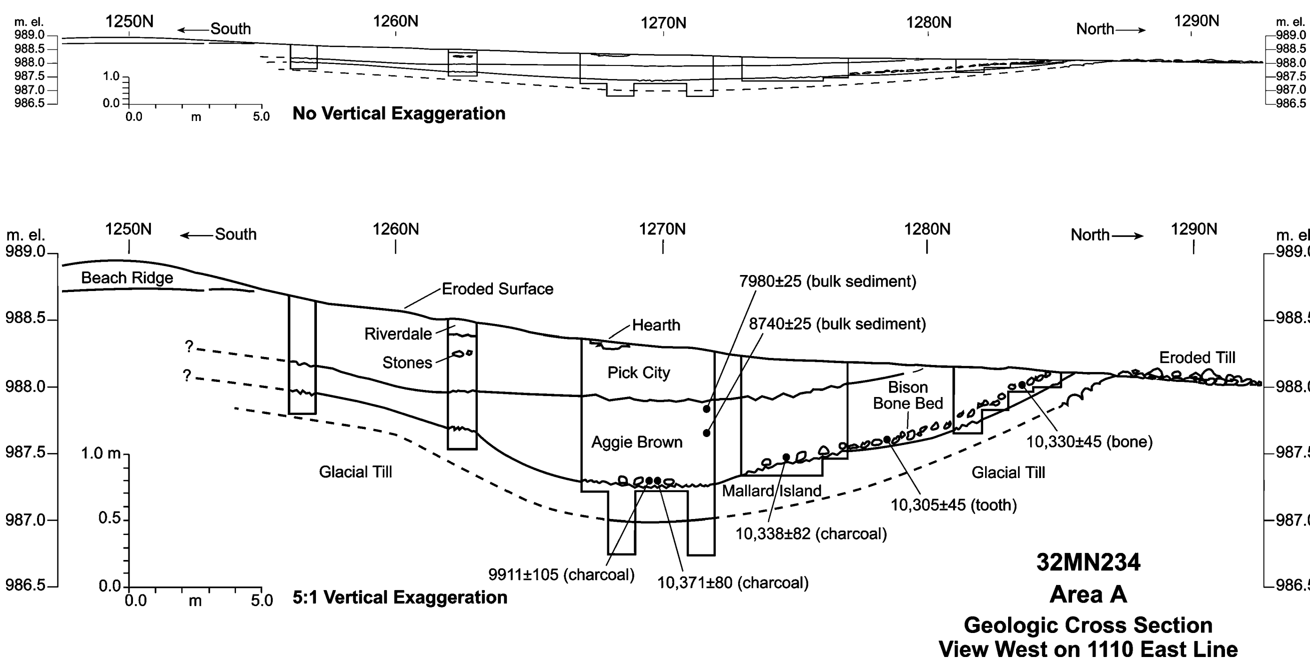
Lake- and other water-basin deposits are usually divided into two general categories: clastic and chemical (Rapp and Hill, 2006, 78). Organic materials can be important constituents of both categories. There is a strong relationship between hydraulic energy and the spatial pattern of coarse- and fine-grained sediment in a lake basin. In general, coarse-grained sediment (sand and gravel) tends to accumulate on the high-energy shoreline at the margin of a lake basin, while fine-grained sediment (silts and clay) and carbonates (limestone and micrite) accumulate near the center of the basin (Figure 2). Organic (carbonaceous) sediment tends to occur along the edges of a basin in quiescent, shallow-water marshes, swamps, and bog settings.

Fluctuating shorelines of lakes and ponds can either bury and protect cultural deposits or erode and destroy them. When water levels are low in a basin, human occupation can occur in locations that can be buried when rising waters submerge them and then deposit deeper water sediment atop the former land surface. At the Beacon Island site in northwestern North Dakota, a dense concentration of bone representing an Agate Basin (Paleo-Indian) bison kill lies deeply buried near the middle of a small kettle basin and less deeply buried near the rim of the basin (Figure 3) (Mandel et al., 2014). It is likely that the bison were killed and butchered on a previously low shoreline of a shallow kettle pond. During the latter part of the Younger Dryas (ca. 10,300 ^{14}C years BP), as the climate became wetter, the water level rose in the kettle basin, and fine-grained pond sediment buried the bones. Because the skeletal remains are articulated and well preserved, the burial process must have been rapid with little modification of the remains by wave action or other dynamic processes at the kettle margins. The bones were thereby protected from various forms of disturbance (Mandel et al., 2014).

Rising waters in a lake or pond can also result in the erosion of cultural features and redeposition of artifacts that were previously deposited on lower shoreline margins, especially if the rise in water level was slow (Figure 2). By contrast, artifacts and features associated with lake margins that were laid down during high water



Site Formation Processes, Figure 2 Generalized diagram showing spatial patterns of site formation in a lake-basin setting (Modified from Rapp and Hill (2006, Figure 3.9)).



Site Formation Processes, Figure 3 Cross section of area A in the kettle basin at the Beacon Island site, an Agate Basin (Paleo-Indian) bison kill in northwestern North Dakota. Because the portion of the bone bed consisting of articulated bison remains extends down the north slope of the basin toward the middle of the depression, it is likely that the bison were killed and butchered on the former low shoreline of a shallow kettle pond. The few bison bones recorded in the middle of the basin probably were eroded from the main bone bed and redeposited (From Mandel et al. (2014)).

levels in the basin will not be affected by wave-driven shoreline erosion during intervals of low water levels; however, other erosional processes, such as gullying and deflation, may disturb artifacts and features on high, abandoned shorelines.

Glacial systems

In some areas of the world, Quaternary glaciation affected the spatial pattern of prehistoric human occupation and the vertical and horizontal integrity of their cultural materials and features. Pleistocene glaciers covered vast areas of land, where they both eroded landscapes and deposited large volumes of sediment. Rapp and Hill (2006, 86) noted that "The growth and melting of continental and mountain glaciers, and the related environmental changes that occurred with these fluctuations, influenced the habitability of certain areas." In glaciated regions, glacial and other processes also determined whether the material remains of humans would be preserved or destroyed.

Glaciers are moving masses of ice that erode and scour the land surface and in the process transport and deposit sediments. Coarse- and fine-grained sediment that becomes incorporated within the mass of ice is transported across the landscape and eventually deposited as till. Till comprises several types of landform, including moraines, drumlins, and till plains. The glacial meltwater that flowed on and under the ice also transported sediment and produced landforms such as eskers, kames, and outwash fans and plains consisting of stratified, well-sorted glaciofluvial deposits. Where meltwater flowed into ice-margin seas or lakes, kame deltas formed. These sedimentological contexts were frequent locations of prehistoric occupation, but such cultural deposits could be destroyed, modified, or preserved by various processes directly or indirectly associated with glaciation (Rapp and Hill, 2006, 87).

Where glaciers moved over landscapes that were once occupied by prehistoric people, archaeological sites were severely eroded or completely destroyed, and artifacts they contained were often incorporated into the glacial sediments and eventually redeposited. Consequently, artifacts associated with an earlier cultural period may occur in deposits of a later (younger) glacial advance. The site of High Lodge in England is a good example of how temporally inverted cultural materials appear in sequences of glacial deposits. At High Lodge, Middle Paleolithic (Mousterian) artifacts were found beneath glacial deposits containing older Acheulean hand axes (Ashton et al. 1992; Roe, 1993; West et al., 2014). It was eventually discovered that neither the Acheulean nor the later Middle Paleolithic artifacts were in situ. The Middle Paleolithic artifacts were contained within fine-grained proglacial lake deposits that were ripped up by advancing ice and transported as large, intact blocks of sediment. The blocks, still containing artifacts that retained their initial integrity, were deposited on top of younger proglacial lake deposits (West et al., 2014). While the Middle Paleolithic lithic artifacts looked fresh and some could be refitted to one another, they were in a disturbed context because they had been transported away from their original locus of deposition within the blocks of matrix that encased them. Subsequently, the older Acheulean artifacts were eroded from a site and transported as part of glaciofluvial and debris-flow materials that buried the deposits containing the transported Middle Paleolithic artifacts. Hence, all of the Paleolithic cultural deposits at High Lodge are in a secondary context.

Late Pleistocene periglacial (ice-marginal) landscapes of North America have yielded a number of stratified archaeological sites. Good examples of these are the Hebior and Schaefer sites in southeastern Wisconsin (Overstreet and Kolb, 2003). These sites are about 3 km apart and lie in a topographic low between two late Wisconsinan end moraines. At both Hebior and Schaefer, a bone pile representing a single mammoth rests on deglacial deposits and is encased in postglacial deposits. At Hebior, the deglacial deposits on which the bones rest consist of glaciolacustrine clays overlain by a thin stratum of glaciofluvial sands, and the overlying postglacial deposits are laminated peat and muck. At the Schaefer site, the bone pile rests on glaciolacustrine clays and is encased in clastic pond deposits together with laminated peat and muck. Based on contextual analysis, the bone piles were preserved initially by inundation within proglacial ponds and subsequently by organic deposition in wetlands. Radiocarbon ages, stratigraphic and geomorphic contexts, and taphonomic studies indicate that both the Hebior and Schaefer mammoths are in situ evidence for human interaction with megafauna very near the active glacial ice margin in the mid-continent by 12,500 ^{14}C BP and perhaps as early as 13,500 ^{14}C BP (Overstreet and Kolb, 2003).

Although the bone piles at the Hebior and Schaefer sites are remarkably well preserved, many processes active in periglacial settings tend to modify such cultural deposits. Most of these processes were associated with seasonal temperature fluctuations. For example, thawing of ground ice would cause disturbance of the surrounding matrix. Other site-disturbance processes included movement of unconsolidated surficial materials over partly frozen ground (solifluction), cryostatic pressure (involutions and cryoturbation), and glaciofluvial processes that were active at peaks during the thaw seasons.

Coastal marine systems

The coastal zones of oceans and seas are critical settings of past human occupation. Such transitional zones between land and water are among the most dynamic of landscape settings, with relative sea level, wave and tide energy, and sediment flux varying on time scales from seconds to millennia (Wells, 2001, 149). Also, depositional environments on the margins of oceans and seas vary over relatively short distances and include beaches, sand dunes, spits and bars, and river-mouth bars and deltas. Changes in the level of the water caused by eustatic and isostatic processes or tectonic forces can either submerge these environments or leave them "stranded" as abandoned shorelines (Rapp and Hill, 2006, 90). Hence, archaeological sites in coastal zones may be affected by an array of terrestrial and marine sedimentary processes. In addition, many of the postdepositional processes described below can modify the vertical and horizontal integrity of the cultural deposits. Defining site formation processes in coastal zones can, therefore, be a challenging task.

Coastal shoreline processes tend to erode or bury cultural deposits. Progradational shoreline sequences, in which land surfaces accrete in a seaward direction, can create a time-transgressive assemblage of sites on and near beaches, with the sites becoming progressively older with increasing distance from the modern boundary between land and water. On the other hand, transgressive episodes where the sea encroaches onto the land can cause beach erosion and destruction of archaeological sites. Archaeological materials eroded from a site may be redeposited on a shoreline and subsequently buried by nearshore sediments, thereby creating a new "site" that lacks in situ cultural deposits.

Archaeologists working in coastal areas around the world have long recognized the destruction of sites caused by marine erosion. For example, on the Channel Islands off the coast of California, natural agents are actively affecting archaeological sites, especially sea-cliff retreat caused by wind and water erosion (Rick et al., 2006). The net effect of daily tidal surges and periodic storms is the loss of many of the island's sea cliffs and headlands every year. Also, strong storms during El Niño and other meteorological events deplete the sand on many island beaches, making marine erosion particularly severe. Numerous stratified archaeological deposits occur on top of many of the island's eroding sea cliffs or along the shoreline (Rick et al., 2006). Although sea-cliff retreat rates vary across space and time, Muhs (1987, 566) suggested that most California sea cliffs retreat at rates averaging between about 0.01 and 0.05 m per year, with much of the retreat occurring during storms and other high-energy events, such as tsunamis.

Tsunamis can result in erosion or burial of cultural deposits. For example, McFadgen (2007) noted how tsunamis completely disarticulated prehistoric Maori village sites on the New Zealand coast. By contrast, late prehistoric sites at the mouths of the Salmon and Nehalem Rivers on the northern Oregon coast were buried by sediment that was transported and deposited by a landward-directed surge of water probably caused by a tsunami (Minor and Grant, 1996).

Waves generated by strong storms can also affect cultural deposits on shorelines. At the Inupiat site of Pingasagruk in northern Alaska, the spatial pattern of prehistoric and historic artifacts appears to be a product of storm surges and associated erosion and transport (Reinhardt, 1993). Rapp and Hill (2006, 95) noted that storm waves erode and transport small artifacts from dunes, often leaving behind larger objects on the beach. They pointed out that "Artifacts eroded from cultural deposits tend to accumulate in secondary concentrations because eddies and turbulence prevent them from washing away. Artifacts like bone, antler, and ivory become waterborne, tumbled, and rolled around before they are redeposited." In addition to being spatially displaced, artifacts transported away from their original location on a beach can be temporally mixed.

Coastal areas that are currently submerged were often areas of human occupation during times of lower sea level. For example, large expanses of continental shelves were dry during the last glacial maximum, about 20,000 years ago. During the terminal Pleistocene and early Holocene, climatic warming melted continental ice sheets and caused global sea level to rise, flooding portions of the shelves and submerging many archaeological sites. This has been confirmed by the discovery of submerged Archaic sites on the continental shelf of North America (Stright, 1995). Also, Paleo-Indian sites have been recorded offshore in the Big Bend region of the Gulf Coast of northwest Florida (Faught, 2002–2004). In some cases, submerged cultural deposits are relatively intact. Early Holocene Mesolithic sites off the coast of Denmark yielded well-preserved organic artifacts (Andersen, 1987; Bailey and Parkington, 1988; Skaarup and Grøn, 2004), as did the submerged Neolithic village of Atlit-Yam off the coast of Israel (Galili and Nir, 1993). Discovery of Acheulean hand axes in Table Bay, South Africa, indicates that some submerged prehistoric deposits can persist for hundreds of thousands of years and remain intact despite several fluctuations in sea level (Werz and Flemming, 2001).

Certain marine contexts strongly favor the preservation of submerged prehistoric archaeological sites (Flemming, 1983; Stright, 1995; Gusick and Faught, 2011). In many cases, structural or geomorphic features of the shoreline allow for preservation of sites (Fedje and Christensen, 1999, 650). For example, coastal caves and rock-shelters have proven to be ideal locations for prehistoric occupation (Erlandson, 1993; Dixon et al., 1997; Fujita and Poyatos de Paz, 1998; Gruhn and Bryan, 2002; Fedje et al., 2004), and these recesses offer some protection from wave and tidal action in a submerged environment (Inman, 1983; Gusick and Faught, 2011). Faught (2002–2004) has shown that submerged karst features, such as those in the Gulf of Mexico, usually contain well-preserved archaeological evidence. Also, shallow bays tend to impose a limited amount of site disturbance from tidal action or storm surges, and site protection from wave energy often occurs on the leeward side of coastal islands and within archipelagos (Flemming, 1983, 138). Gusick and Faught (2011, 36) noted that "Coastlines with gently sloping continental shelves, particularly in locales with reduced wave action, would have been quickly inundated during sea level rise, promoting rapid sedimentation and therefore protection of archaeological sites from environmental elements." According to Dean et al. (1992, 31) and Muckelroy (1978, 52), the anaerobic environment that often occurs in the seabed is favorable for the preservation of organic material associated with archaeological sites.

Even in regions in which conditions are generally favorable for preservation of submerged archaeological sites, various geologic, oceanographic, and meteorologic factors may compromise the preservation of cultural deposits (Gusick and Faught, 2011). While the geomorphology of eastern Pacific coastal environments is characterized by rocky shores and deep basins that provide enclaves and rock-shelters generally favorable for the protection of submerged archaeological sites, the powerful wave action in this area of the world can erode away sea cliffs and cut marine terraces (Inman, 1983; Gusick and Faught, 2011), thereby destroying evidence of prehistoric occupation. In areas with reduced wave action, such as the Gulf of Mexico and Gulf of California, site preservation may be more likely than those areas exposed to the open ocean, but the frequent hurricanes that occur in these regions may destroy or severely modify submerged cultural deposits (Gusick and Faught, 2011).

Stewart (1999) noted that for shipwrecks and coastal archaeological sites, once submergence occurs, the single most important factor for preservation is rapid deep burial by sediment. A thick mantle of sediment "protects the artifacts themselves and their spatial patterning from destruction by water and marine organisms" (Stewart, 1999, 565). When shipwrecks and sites are on the seafloor or shallowly buried in marine deposits, they may be modified or destroyed by natural and/or anthropogenic processes. A range of marine animals that live on the seafloor, such as crabs and lobsters, are known to burrow into sediment, and their burrowing activity can disturb artifacts (faunalturbation) and allow a greater amount of oxygen to penetrate into bottom sediment via their burrows (Stewart, 1999). Oxygenation, in turn, can promote bacterial growth and thereby cause degradation of organic artifacts. Also, the roots of benthic marine plants, especially ubiquitous sea grass, can disturb cultural deposits (floralturbation). Common anthropogenic processes that affect shipwrecks and submerged sites include salvaging, treasure hunting, dredging, and offshore construction.

Postdepositional processes

After artifacts and cultural features are emplaced on the land surface, physical and chemical processes may alter the spatial and compositional character of the archaeological deposits (Leigh, 2001). The major physical (geologic and biologic) processes that can affect the spatial distribution of artifacts are mass movement and pedoturbation. With mass movement, materials move downslope mostly under the influence of gravity, though water may lubricate and assist in the transport. Mass movement may be a slow process, such as creep, solifluction, and subsidence, or it may be rapid, as is the case with mudflows, landslides, and rockfalls (Rapp and Hill, 2006, 99). Pedoturbation, or soil mixing, includes a variety of processes driven by different vectors (Table 1).

Common postdepositional chemical processes that affect cultural deposits include oxidation, carbonation, and humification. These processes generally are associated with weathering and soil formation, and they involve water and other soluble components in soil solution. In archaeological settings, the consequences of chemical weathering are the breakdown or decomposition of lithic and metal artifacts, ceramics, and organic materials, such as bone, shell, and wooden artifacts.

Postdepositional alteration of cultural deposits is frequently attributed to pedoturbation. Bioturbation is one of the most common forms of pedoturbation and often affects archaeological sites. There are two general categories of bioturbation, floralturbation and faunalturbation, which are the mixing of soil and sediment by plants and animals, respectively. Floralturbation processes that affect cultural deposits are mostly associated with trees. Schiffer (1987) noted that, in wooded areas, artifacts and features are often displaced or severely damaged by tree roots soon after site abandonment. Tree roots put tremendous pressure on objects in the soil (Wood and Johnson, 1978; White, 1979), and the in situ disintegration and decay of large, deep tree roots contributes to the vertical movement of artifacts through the soil profile. Root decay produces hollow cavities and tunnels that may collapse, subsequently filling with younger sediments (Macphail and Goldberg, 1990). As the root cavity fills, artifacts at the surface may fall into the root hole thereby becoming translocated and buried within the substrate (Waters, 1992, 309).

Trees are even more destructive when they are blown over by the wind, a process known as tree throw (Schaetzl et al., 1990; Waters, 1992, 307; Rapp and Hill, 1998, 83–84). When a tree throw occurs, the soil and archaeological material entwined in the roots are pulled away from the substrate, leaving a shallow, craterlike depression. Eventually, the soil and cultural debris adhering to the root mass fall back into the depression or accumulate in a mound adjacent to the crater. In a matter of several 100 years, tree throws can significantly rework surface sediment in forested areas. The constant churning of the soil resulting from this process can destroy the spatial patterning of cultural deposits at a site (Waters, 1992, 307). On relatively stable geomorphic surfaces, artifacts may become buried when they fall into tree-throw craters. Holmes (1893) demonstrated that buried artifacts collected from glacial till at the Babbitt site in Minnesota were translocated downward to a depth of more than 1.25 m by tree throws.

Faunalturbation is caused by a variety of fossorial (burrowing) animals, including mammals, earthworms, ants, termites, and other arthropods. Fossorial mammals include small rodents such as gophers, mice, moles, prairie dogs, ground squirrels, gerbils, and cavies as well as larger animals like beavers, foxes, badgers, rabbits, and armadillos. Several studies have shown that burrowing mammals turn over a large quantity of soil and sediment annually (Bocek, 1986; Ohel, 1987; Wood and Johnson, 1978). During burrow construction and maintenance, they commonly move smaller artifacts up while burrowing

Site Formation Processes, Table 1 Major types of soil and sediment disturbance/mixing and the general direction of artifact movement

Process		Type of disturbance or mixing process	General direction of artifact movement
Alluvial		Natural: displacement by stream flow	Downstream. Also, winnowing of fines resulting in superposition of artifacts
Eolian		Natural: displacement by wind	The direction of the wind. Also, winnowing of fines resulting in superposition of artifacts
Mass movement/ graviturbation		Natural: displacement by slope processes, such as solifluction, creep, and landslides	Downslope
Cryoturbation		Natural: mixing by freeze-thaw activity	Up and laterally in sediment
Argilliturbation		Natural: mixing caused by shrink-swell processes associated with expandable clay minerals	Up and down
Aquaturbation		Natural: mixing by water moving forcefully through soil or sediment, such as a spring boil	All directions
Crystalturbation		Natural: mixing by the growth and wastage of crystals, such as salt, gypsum, and ice	All directions
Impacturbation		Natural and anthropogenic: mixing when large objects strike the ground. Includes bombs that hit the ground and explode	All directions
Seismiturbation		Natural: mixing by earthquakes and the surficial settling that occurs after them	Down
Bioturbation	Faunalturbation	Natural: mixing by the activities of burrowing animals	Small artifacts tend to move up and large artifacts tend to move down. With biomantle formation, all artifacts can be buried and appear to move down
	Floralturbation	Natural: mixing by the activities of plants	Root growth: all directions Root decay: down Tree throw: all directions and can cause inverted stratigraphy and mixing of assemblages
Trampling		Natural and anthropogenic: displacement by animals or people walking on soil or sediment	Down
Digging		Anthropogenic	Selected artifacts removed, others redeposited randomly
Collecting		Anthropogenic	Selected artifacts removed, others redeposited randomly

Sources: Schaetzl and Thompson (2015) and Goldberg and Macphail (2006)

under larger objects. Eventually the larger objects collapse into the burrow, moving them down in the profile (Bocek, 1986, 591). As a result of this process, some "observable stratigraphy" may actually represent rodent-related "horizons" (Bocek, 1986, 601). In some cases, one type of animal disturbance can attract another fossorial animal. For example, the matrix of krotovina (soil-filled animal burrows) typically has a lower bulk density and is softer than the surrounding soil or sediment. Consequently, worms are attracted to the krotovina, and their actions account for substantial mixing of material across the boundaries of the original burrow (Pietsch, 2013).

A number of studies have reported how earthworms bury surface-occurring artifacts and features beneath their castings (Darwin, 1881; Shaler, 1891; Atkinson, 1957; Wood and Johnson, 1978; Rolfsen, 1980; Stein, 1983; Johnson and Watson-Stegner, 1990; Balek, 2002; Johnson, 2002; Van Nest, 2002; Peacock and Fant, 2002; Canti, 2003). Rolfsen (1980), for example, demonstrated that earthworms can bury items to a depth of 45 cm below ground surface in about 5 years. Hence, worm castings, combined with soil brought to the surface by ants, burrowing mammals, and uprooted trees, form a biomantle that may quickly conceal artifacts and cultural features on otherwise stable surfaces (Johnson, 1990; Johnson, 1992; Van Nest, 2002). Biomantle formation eventually results in the gradual burial and "downward gravitational displacement" of materials that originally lay on the surface (Balek, 2002, 43). Several researchers have described the role that biomantle formation plays in the burial of upland archaeological sites (e.g., Leigh, 2001; Balek, 2002; Bettis and Mandel, 2002b; Johnson, 2002; Peacock and Fant, 2002; Van Nest, 2002; Johnson et al., 2005).

Other natural mixing processes that often contribute to the disturbance of cultural deposits are cryoturbation and geliturbation. Cryoturbation is associated with permafrost and seasonally frozen ground and is the mixing of soil and sediment by freeze-thaw activity, as ice crystals repeatedly form and melt. Seasonal freezing and thawing of the ground causes buried objects to move up through a soil profile and horizontally across the ground surface (Johnson and Hansen, 1974; Wood and Johnson, 1978; Bowers et al., 1983; Van Vliet-Lanoë, 1985; Bertran, 1993; Bertran, 1994; Van Vliet-Lanoë, 1998). In a series of experiments, Johnson and Hansen (1974) and Johnson et al. (1977) demonstrated that in a single cold season, freeze-thaw action can vertically displace an artifact as much as 10 cm. According to Bowers et al. (1983), such displacement can be as great as 20 cm.

In addition to frost heaving, cryoturbation produces frost cracks and involutions (deformation structures) in soils and sediments. The effect of frost cracks on cultural deposits is similar to that of cracking produced in vertisols (see below), which allows artifacts to be displaced downward and mixed lower in the soil or body of sediment. The formation of involutions, including undulations or folds, also may displace artifacts.

Because seasonally frozen ground affects nearly 50 % of the land area of Earth (all high latitudes and most middle latitudes) (Holliday, 2004, 278), cryoturbation has a significant global impact on cultural deposits. Schweger (1985, 127) considered this impact, noting that "The greatest handicap to northern archaeology is frost disturbance and its effects on archaeological matrix and the artifacts themselves." Case histories of cryoturbation effects on soils in archaeological contexts, however, are relatively rare (Holliday, 2004, 278), though reviews by Bobrowsky et al. (1990), Thorson (1990), and Wilson (1990) provide examples.

Geliturbation, which also occurs in regions where there is permafrost, is a product of gelifluction (also called solifluction), the slow downslope movement of saturated soil above permafrost. Gelifluction usually involves large saturated masses (lobes) of soil whose cohesive forces have been weakened by repeated freeze-thaw activity; it can occur on very gentle slopes (Schaetzl and Thompson, 2015, 257). This process causes dramatic involutions of surface horizons of soils and is widely reported from cold-climate archaeological sites (e.g., Thorson and Hamilton, 1977; Schweger, 1985; Thorson, 1990). Gelifluction can significantly affect archaeological sites by burying cultural deposits, transporting artifact downslope, and/or inverting cultural horizons. For example, at the Iyatayet site on Cape Denbigh, on the west coast of Alaska, the type Denbigh Flint Complex was found in a buried A horizon of a podzolic soil (Hopkins and Giddings, 1953). The soil and associated cultural deposits had been completely folded by gelifluction lobes before burial.

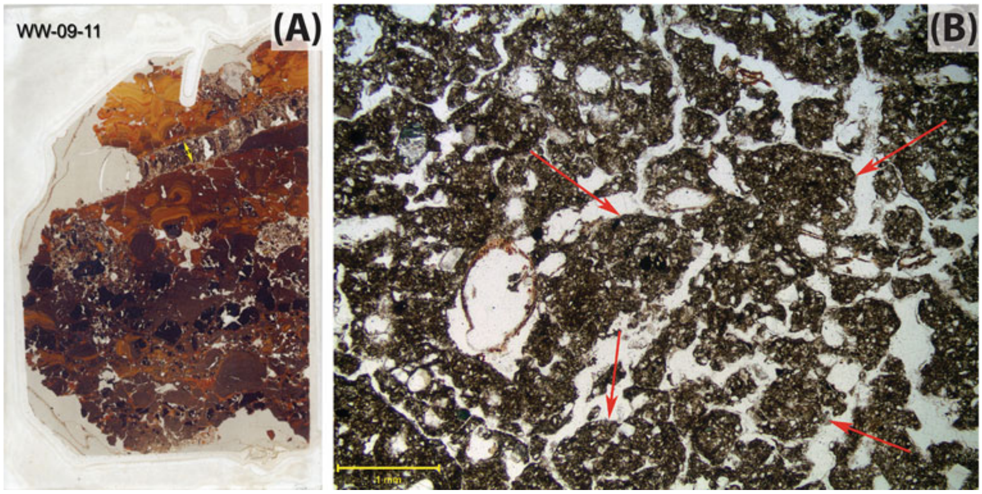
Argilliturbation is another common form of pedoturbation that involves the mixing of soil as a result of the shrinking and swelling of expandable clay minerals, such as smectite. Expandable clays tend to shrink during dry periods, causing large vertical cracks to form at the surface. These cracks are usually <10 cm deep, but under very dry conditions, they can reach depths of over one meter. Artifacts and other surface material can fall into these cracks when they are open. As the moisture content in soil increases, the expandable clay minerals swell, and the cracks close. This process results in the burial of any artifacts that fell into the cracks (Wood and Johnson, 1978; Schiffer, 1987).

Soils defined by extreme amounts of argilliturbation due to high amounts of smectite clays, in a wet-dry climate, are designated as vertisols in the USDA-NRCS system of soil classification (Soil Survey Staff, 2014). The name is derived from the Latin *vertere*, "to turn over or invert." Soils that have high shrink-swell capability but that do not meet the qualifications of vertisols are described as "vertic."

The mixing processes associated with vertisols and vertic soils can have significant effects on artifacts and cultural features. Vertisols are capable of forcing buried artifacts up to the surface and providing pathways for surface materials to move down into the soil (Holliday, 2004, 276). Duffield (1970, 1055), an archaeologist who excavated sites in vertisols in east central Texas, described the effects of these soils, noting that they can "churn archaeological features into a homogeneous mass and totally destroy the original context of a site." At the Cave Spring site in Tennessee, Hofman (1986) determined that artifacts spanning 7,000 years of prehistory were moved vertically 20–40 cm in a buried soil with vertic properties. During the excavation of a site on Crete, Morris et al. (1997) recorded Middle Minoan period artifacts on the surface of a vertisol and at depths of 30–100 cm. Based on the results of laboratory analyses, they concluded that there were no buried Minoan living surfaces and that the artifacts moved downward through cracks in the vertisol.

Field observations (such as documenting the location and angle of repose of artifacts) and recording the abundance and spatial pattern of disturbance features (such as krotovina) are necessary to determine whether the vertical and/or horizontal integrity of cultural deposits has been compromised by processes of postdepositional mixing. Physical evidence of disturbance must be precisely recorded in the field so the information can be used during analysis of the site and assessment of the integrity of the archaeological materials. In some cases, laboratory methods, including grain-size analysis, soil micromorphology (Figure 4), scanning electron microscopy (SEM), three-dimensional scanning, and numerical dating, can help identify soil and sediment disturbances that are not easily detected in the field (Leigh, 2001; Goldberg and Macphail, 2008; Grosman et al., 2011). Information gleaned from laboratory analyses can be used both to identify disturbances and corroborate field observations of depositional and postdepositional processes (Goldberg and Macphail, 2008). Refitting of artifacts and/or bone can also inform researchers about disturbance, even when there are no visible signs of disturbance (Villa, 1982, 287). However, refitting evidence must be used with caution, because the presence of conjoinable items does not mean disturbance has not occurred (Schick, 1987, 102). Hence, refitting evidence is best used in combination with other methods to assist in identifying site disturbances.

According to Michie (1990), several aspects of the archaeological record are indicative of postdepositional mixing processes, especially bioturbation. They include the following:



Site Formation Processes, Figure 4 (**a**) Thin-section scan of pre-cultural deposits at Wonderwerk Cave, South Africa. The contorted phreatic deposits shown here have been penetrated by a 1-cm-wide biotubule (*arrow*). The thin section measures 50 × 75 mm, plane-polarized light (*PPL*), from Goldberg et al. (2015). (**b**) Photomicrograph of a thin section from the upper 10 cm of the ABb horizon at site 32RY473, a heavily bioturbated, multicomponent Woodland occupation located on a beach ridge at Devils Lake in northeastern North Dakota. Note the parts of earthworm casts (*arrows*) and granular matrix (PPL) (From Mandel and Goldberg (2011)).

1. A strong relationship exists between the maximum artifact depth and the visible depth of pedoturbation; for example, artifacts do not continue below the deepest krotovina or root well.
2. Artifacts are oriented >0–90° to the horizontal, i.e., not resting flat on former surfaces.
3. There is an absence of intact cultural features such as hearths.
4. Vertical and horizontal displacement separates artifacts that would otherwise be found together.
5. Evidence of a single behavior activity (i.e., core reduction) or artifact (broken pot) is found mixed throughout the soil.

Michie (1990) also argued that stratified cultural horizons often reveal vertical translocation of artifacts, suggesting that older artifacts have more time to descend within the profile through bioturbation even while vertical separation between cultural strata remains relatively intact. This contrasts with other models (e.g., Bocek, 1986) that point to postdepositional mixing processes as driving forces that modify archaeological deposits while obliterating original features such as primary bedding.

Leigh (2001) considered Michie's (1990) model and noted that the degree of vertical separation of cultural material probably depends on two factors: the types of burrowing organisms that have operated at the archaeological site and the grain-size distribution of the sediment. Leigh (2001, 281–282) points out that "Ants and worms are not capable of moving large artifacts up to the ground surface, which may help preserve vertical separation of cultural strata, whereas larger animals (i.e., gophers, tortoises) are capable of bringing artifacts larger than 3 cm up to the surface. Thus, while the overall integrity of cultural stratigraphy may remain intact, some degree of mixing is to be expected."

Caves and rock-shelters

Archaeological research has focused on caves and rock-shelters for more than a century, especially in Europe (Bordes, 1972; Goldberg and Mandel, 2008). Caves and rock-shelters have yielded significant components of the early archaeological record, including fossil hominins, faunal and floral remains, and extensive assemblages of lithic tools. Some of the earliest evidence of fire use comes from Wonderwerk Cave in South Africa (Berna et al., 2012; Goldberg et al., 2015), Zhoukoudian in China (Goldberg et al., 2001), and Qesem Cave in Israel (Karkanas et al., 2007), as well as from Middle Paleolithic cave sites in Europe (e.g., Abric Romaní (Vallverdú et al., 2012) and Roc de Marsal (Goldberg et al., 2012; Aldeias et al., 2012)) and the Middle East (e.g., Kebara Cave (Meignen et al., 2007)). Caves and rock-shelters also have been the focus of archaeological research concerned with the peopling of the New World, especially South America. Cave sites in the Peruvian Andes, including Telarmachay, Uchumachay, Lauricocha, Huargo, Guitarrero, Pachamachay, Pikimachay, and Panaulauca, have yielded finds suggesting that people were in the region as early as 20,000–15,000 BP, and in eastern Brazil, the rock-shelter at Pedra Furada has produced disputed evidence for human occupation over 30,000 years ago.

Caves and rock-shelters are commonly associated with karstic processes involving dissolution and precipitation of carbonates. However, they can also be found in noncalcareous bedrock, including sandstone (e.g., Meadowcroft Rockshelter (Donahue and Adovasio, 1990)) and quartzites (e.g., numerous sites in South Africa (Marean et al., 2000; Marean et al., 2010; Karkanas and Goldberg, 2010)). In the Great Basin of North America, rock-shelters are associated with former shorelines of pluvial lakes where wave action has created or enlarged them (Rhode et al., 2005; Goebel et al., 2007; Jenkins, 2007). Farther north, on the Snake River Plain of eastern Idaho, caves are often associated with collapsed lava tubes (e.g., Owl, Coyote, and Dry Cat caves comprising the Wasden site (Moody and Dort, 1990)). Also, rock-shelters form by fluvial undercutting of bedrock valley walls. As an illustration, Bonfire Shelter in southwest Texas is a product of fluvial undercutting of a cliff face in Mile Canyon when the elevation of the canyon floor was 18 m higher than it is today (Dibble and Lorrain, 1968).

Depositional processes

Unlike open-air sites, which are open depositional systems, caves and rock-shelters are closed or nearly closed systems. In most cases, what enters the cave/rock-shelter tends to stay there, and thus these sites safeguard detailed records of geologic processes and human activities. However, despite being relatively protected, caves, and especially rock-shelters, are not always isolated from geomorphic and biological processes that may reshape cultural deposits in these settings, and their sedimentary deposits can be subject to physical and chemical modifications (see below).

Sediments derived from within the cave/rock-shelter environment are locally formed, i.e., autochthonous (Goldberg and Sherwood, 2006), and a main depositional process that creates them is attrition – the grain-by-grain disintegration of sandstone or bioclastic limestone, which produces a steady rain of sediment to the floor of a cave or rock-shelter (Donahue and Adovasio, 1990; Mandel and Simmons, 1997) or the accumulation of larger rock and roof fall, *éboulis* (Laville et al., 1980). In both cases, material can be dislodged from the bedrock and deposited on the cave or rock-shelter floor as a result of any one of a number of processes, including hydration, freeze-thaw, salt and solution weathering, and tectonics.

Along with the generally coarse autochthonous sediment (sand sized and larger), finer-grained material, such as clay derived from soil outside the cave or rock-shelter, can be introduced by infiltration of dripping water along joints in the bedrock. Such dripping not only results in the formation of distinct layers of clay but also more subtly as clay coatings and void infillings. Clay that enters a cave or rock-shelter from an external source is allochthonous sediment regardless of its geologic context.

Allochthonous sediments found within a cave or rock-shelter that derive from outside are often similar to sediments deposited at open-air sites. When streams are adjacent to or very near valley walls, coarse-grained sediment including sand and gravel may be delivered to rock-shelters and cave mouths through lateral accretion of point bars. In contrast, fine-grained alluvium (mostly silt and clay) held in suspension may be deposited during floods, a process known as vertical accretion. Rodgers Shelter in the western Ozark Highlands of Missouri exhibits a sequence of lateral and vertical accretion deposits (Ahler, 1976). This archaeologically rich shelter remained at or only a few meters above the elevation of the floodplain of the Pomme de Terre River throughout the Holocene. Similarly, the Abri de la Madeleine (Magdalene rock-shelter) in southwestern France, the type site for the Upper Paleolithic Magdalenian culture, is filled with alluvium from the nearby Vézère River (Laville et al., 1980).

Alluvium also occurs in karstic caves. For example, at Sheriden Cave, a Clovis habitation site in Ohio, fine-grained sediments display evidence of alluvial transport. In general, coarser sediments, including sand and fine gravel, were deposited near the cave entrance, and silt and clay were deposited in laminar layers in the lowest passages (Tankersley, 1997).

Eolian sedimentation in caves and rock-shelters includes both sandy and silty inputs. Many Paleolithic and Middle Stone Age sites contain abundant eolian sand deposits, which in most cases are tied to eustatic sea level changes (e.g., Tabun Cave, Israel (Goldberg, 1973); Die Kelders, Blombos, and Pinnacle Point sites in South Africa (Tankard and Schweitzer, 1974; Goldberg, 2000; Marean et al., 2010); Akrotiri *Aetokremnos* Rockshelter, Cyprus (Mandel and Simmons, 1997)). Finer eolian sediment consisting of silt and clay also occurs in caves and rock-shelters, although it normally is not volumetrically significant. Although eolian dust can blow directly into a cave, as was the case at the Middle Paleolithic/Upper Paleolithic sites of Hohle Fels and Geißenklösterle in Swabia, Germany (Hahn, 1988), it is often found in a secondary context, having been reworked and redeposited into the cave by runoff or colluvial processes. Dust Cave in Alabama is a good example of loess from the limestone plateau above the site being colluvially redeposited in the cave (Sherwood et al., 2004). In Paleolithic sites like Kebara, Tabun, Qafzeh, and Hayonim caves in Israel, eolian quartz silt that is embedded in *terra rossa* soils of the surrounding land surface (1) accumulated in the caves as a colluvial apron and/or sheetwash deposit at the entrance or (2) was washed through "chimneys" (dissolution features) that formed in the limestone roof (Goldberg and Bar-Yosef, 1998). In the case of colluvium, the accumulated deposits are poorly sorted and commonly form a berm below the modern or former drip line at the cave entrance. This sediment can be remobilized and carried back further into the cave, as at Dust Cave and Kebara.

Slope deposits consisting of allochthonous sediment are fairly common in rock-shelters and caves. There are two general types of slope deposits: colluvium and sheetwash. The term colluvium is used to describe poorly sorted deposits of sediment transported chiefly by gravity. Sheetwash (or slope wash) is well-sorted laminated

Site Formation Processes, Figure 5 Photograph of modern-day runoff at Kebara Cave, Israel, produced by a thunderstorm in October of 1985. Water is flowing from the entrance to the back of the cave along a depositional slope produced by sediment accumulating at the brow of the cave beneath the overhang. Two 20 l jerry cans are introduced for scale.

sediment that has been moved down a slope predominantly by the action of gravity assisted by water in the form of sheet flow or concentrated flow in rills (Figure 5). Slope deposits may form a berm or talus cone in front of a rock-shelter or cave entrance (Figure 6). From there, they can be washed back into the shelter or cave by runoff or high-density mudflows.

Marine deposits occur in archaeological caves, but they are not particularly common. These deposits usually consist of littoral boulders at the bottom of stratigraphic sequences, as is the case at Gorham's Cave, Gibraltar (Goldberg and Macphail, 2012), or littoral sands, such as those that occur at the bottom of the sequence in Contrebandiers Cave, Morocco (Aldeias et al., 2014).

Human activities represent an understudied aspect of depositional processes in caves and rock-shelters. Human-derived materials are obvious and widespread in caves and rock-shelters around the Mediterranean, especially those with Holocene deposits (Woodward and Goldberg, 2001); however, significant human inputs are also noteworthy from Paleolithic and Middle Stone Age (MSA) sites in the Old World and Africa (Figure 7). Typically, anthropogenic deposits consist of sediments and materials directly related to burning (e.g., hearths, fire-cracked rock, charcoal, ashes, burned soil, and bones), eating (bones and plant remains), and sleeping (material used for mats) or to activities that redistribute sediments and materials, such as hearth rake-out, sweeping, and dumping of ashes and charcoal (Meignen et al., 2007; Miller et al., 2010; Turq et al., 2011; Wadley et al., 2011; Speth et al., 2012). In certain cases, such as Kebara and Hayonim caves in Israel, anthropogenic accumulations constitute the majority of the depositional fill and substantially exceed geogonic contributions. Prominent anthropogenic deposits also have been documented in caves and rock-shelters in the USA, including Dust Cave in Alabama, Movie Draw Rockshelter in the Black Hills of South Dakota, Burntwood Creek Rockshelter on the High Plains of western Kansas, and Danger Cave in the Great Basin region of Nevada (Figure 8).

Another depositional factor that has been underestimated is that of biological additions and modifications. Bat and bird guano are common in modern cave and rock-shelter deposits, but in Pleistocene deposits, it is difficult to detect them directly in the field. However, guano can be documented by micromorphological analysis (Karkanas and Goldberg, 2010; Goldberg and Macphail, 2012). Indirect evidence is more readily apparent in the form of extensive diagenesis in cave deposits, which is clearly brought about by the former presence of bat guano (Karkanas et al., 2000; Weiner et al., 2002) (see below). Other biogenic inputs in caves and rock-shelters include the products of denning activities by carnivores and omnivores (Goldberg and Macphail, 2006, 179). Hyenas and bears, for example, can produce large accumulations of bones, coprolites, and organic matter (Horwitz and Goldberg, 1989; Andrews et al., 1999; Goldberg, 2001; Schiegl et al., 2003).

Postdepositional processes

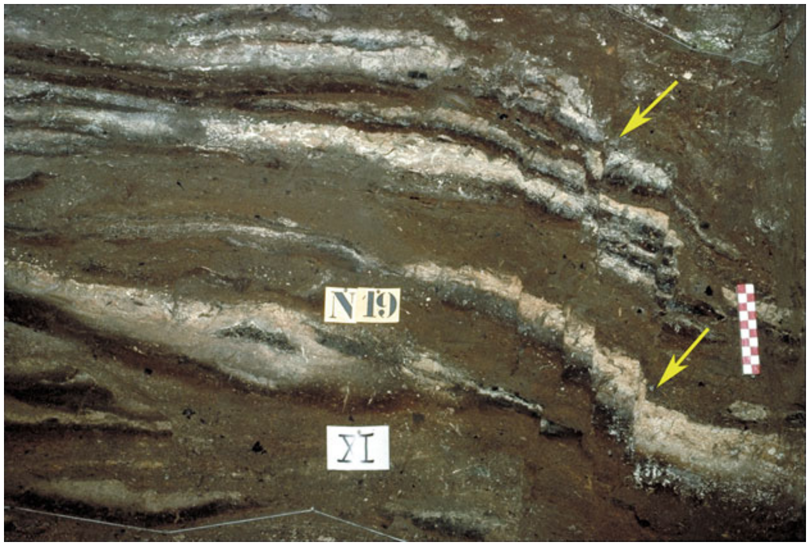
Postdepositional processes, both physical and chemical, are generally described using the term "diagenesis." They are particularly important in caves and rock-shelters where karstic processes and biological additions can seriously alter the nature of the sediments and consequently affect the integrity of the archaeological record. Physical changes can entail movements of bones, lithics, and other anthropogenic components by the depositional processes outlined above, and sheetwash and deflation by wind can transport materials further back into a cave or rock-shelter and, at the same time, selectively sort the materials left behind. Colluviation and slumping can completely displace and dismantle features (e.g., hearths and bedding) or archaeological material from their original positions. Such reworking is readily seen at Dust Cave (Sherwood and Goldberg, 2001) and Kebara Cave (Goldberg et al., 2007). Similarly, ongoing dissolution of limestone caves – roofs, walls, and bedrock floor – can result in differential subsidence and settling of the deposits, expressed as slumping and faulting (Figure 9).

Site Formation Processes, Figure 6 View of the entrance (*arrow*) of Dust Cave, Alabama, located along a limestone bluff face. Visible is a berm of clayey and silty deposits that have washed over the bluff and accumulated as a berm at the cave entrance.

Site Formation Processes, Figure 7 A series of finely bedded combustion layers at Roc de Marsal, a Paleolithic cave in the Dordogne region of France. Similar anthropogenic layers represent most of the deposits at the site.

Site Formation Processes, Figure 8 Early Archaic components (8500–8000^{14}C year BP) at the Danger Cave rock-shelter site in the Bonneville Basin of western Utah contain 5–15-cm-thick beds of well-preserved plant materials (*arrows*), including chaff from pickleweed that was processed in the rock-shelter for its seeds (Photograph courtesy of David Rhode).

Chemical alterations can be important processes in caves and rock-shelters. The most common and well known is the precipitation of calcium carbonate, recognized mostly in the form of stalactites/stalagmites, bedded layers (flowstone/travertine), or massive impregnations of matrix material, so-called cave breccia (Karkanas et al., 2007). A recent study of the Cave 13B deposits at Pinnacle Point, South Africa, revealed massive impregnations of calcite



Site Formation Processes, Figure 9 Combustion layers at Kebara Cave that have been faulted (*arrows*) due to subsidence of the deposits into a karstic cavity. Scale is 20 cm long.

Site Formation Processes, Figure 10 Massively cemented deposits at Cave 13B, Pinnacle Point, Mossel Bay, South Africa. These deposits were cemented at a time of massive root growth producing calcified roots (rhizoliths), which are indicated with *arrows*. Meterstick in the center is 1 m long.

(Figure 10) from an extensive mat system of fine roots (Karkanas and Goldberg, 2010).

In addition, dissolution and mineralogical alterations are common in cave deposits. Guano, organic acids, and associated acidic dripping waters can partially or completely dissolve carbonate, resulting in the formation of other minerals, such as gypsum (Shahack-Gross et al., 2004). In some instances, dissolution can significantly reduce the volume of the original deposits (up to 50 %), as at Die Kelders Cave, South Africa (Goldberg, 2000). In places where extreme diagenesis occurs, major mineralogical transformations can cause the formation of various phosphate minerals, along with the breakdown of clays, and ultimately the neoformation (precipitation) of silica (Weiner et al., 2007). The ramifications of such transformations involve the complete destruction of bone from all or parts of the cave or rock-shelter and concentration of radioactive isotopes. Awareness of such diagenetic changes, therefore, allows for more accurate dating of deposits and a better understanding of the spatial distribution of bone across a site, which may not be related solely to human activities but rather to postdepositional biogeochemical ones.

Methods of analysis

Many of the methods used to unravel site formation processes in caves and rock-shelters are the same as the ones used at open-air sites. Sedimentological analyses typically include a relatively standardized set of analytical techniques, such as grain-size analysis, assessment of clast and grain morphology, analysis of heavy minerals (those with high specific gravities), and other mineralogical analysis using X-ray diffraction. A number of chemical analyses are also employed, such as measuring the amount of organic matter, calcium carbonate, and phosphate. These analyses are typically conducted on bulk samples collected from primary stratigraphic units.

Over the past several decades, micromorphology has become a powerful tool used by geoarchaeologists to study site formation processes in caves and rock-shelters (Courty et al., 1989; Goldberg and Macphail, 2006). This approach involves the examination of intact blocks of sediment under the petrographic microscope. The analysis of thin sections enables the researcher to observe mineralogical composition, size and shape of the particles, and the finer matrix. More importantly, because the original geometry of the components within the sample is preserved, it is possible to isolate depositional effects from postdepositional ones. Thus, original calcite from limestone *éboulis* can be distinguished from secondary (precipitated) accumulations of carbonate, and phosphates from bones can be distinguished from neoformed ones. Also, subtle biogenic features that are not visible to the naked eye can be detected in thin sections, thereby allowing the magnitude of bioturbation to be fully assessed.

Although micromorphology has been effectively used in many studies of site formation processes in caves and rock-shelters, optical microscopy has its limits, and more sophisticated analytical techniques are now more commonly combined with micromorphological analysis, particularly in the study of diagenesis, the stratigraphic integrity of cultural deposits, the reliability of radiocarbon and OSL ages, and the relative amount of geogonic versus anthropogenic sediments. For example, high-resolution stratigraphic and sedimentary analysis, including Fourier transform infrared (FTIR) spectrometry and FTIR microspectroscopy (μ-FTIR), and x-ray microfluorescence (μ-XRF) (Mentzer and Quade, 2013) have proven to be invaluable tools in evaluating the type and extent of diagenesis in archaeological contexts within caves and rock-shelters (e.g., Goldberg and Sherwood, 2006; Schiegl and Conard, 2006; Karkanas and Goldberg, 2007; Berna and Goldberg, 2008; Goldberg et al., 2009; Feathers et al., 2010; Mallol et al., 2010; Weiner, 2010; Wadley et al., 2011; Berna et al., 2012; Miller et al., 2013). Also, "in situ" study of materials within thin section has been enabled with the use of μ-FTIR techniques that permit, for example, evaluation of the degree of heating of bones and clays from prehistoric fireplaces (Berna et al., 2007; Berna and Goldberg, 2008; Jordá Pardo et al., 2008; Berna, 2010; Goldberg and Berna, 2010).

Bibliography

Ahler, S. A., 1976. Sedimentary processes at Rodgers Shelter. In Wood, W. R., and McMillan, R. B. (eds.), *Prehistoric Man and His Environments: A Case Study in the Ozark Highland*. New York: Academic, pp. 123–139.

Aldeias, V., Goldberg, P., Sandgathe, D., Berna, F., Dibble, H. L., McPherron, S. P., Turq, A., and Rezek, Z., 2012. Evidence for Neandertal use of fire at Roc de Marsal (France). *Journal of Archaeological Science*, **39**(7), 2414–2423.

Aldeias, V., Goldberg, P., Dibble, H. L., and El-Hajraoui, M., 2014. Deciphering site formation processes through soil micromorphology at Contrebandiers Cave, Morocco. *Journal of Human Evolution*, **69**, 8–30.

Andersen, S. H., 1987. Tybrind Vig: a submerged Ertebolle settlement in Denmark. In Coles, J. M., and Lawson, A. J. (eds.), *European Wetlands in Prehistory*. Oxford: Clarendon, pp. 253–280.

Andrews, P., Cook, J., Currant, A., and Stringer, C. (eds.), 1999. *Westbury Cave: The Natural History Museum Excavations, 1976–1984*. Centre for Human Evolutionary Research at the University of Bristol (CHERUB). Bristol: Western Academic and Specialist Press.

Ashton, N., Cook, J., Lewis, S., and Rose, J. (eds.), 1992. *High Lodge: Excavations by G. de G.. Sieveking, 1962–8, and J. Cook, 1988*. London: British Museum Press.

Atkinson, R. J. C., 1957. Worms and weathering. *Antiquity*, **31**(124), 219–233.

Bailey, G., and Parkington, J., 1988. The archaeology of prehistoric coastlines: an introduction. In Bailey, G., and Parkington, J. (eds.), *Archaeology of Prehistoric Coastlines*. Cambridge: Cambridge University Press, pp. 1–10.

Balek, C. L., 2002. Buried artifacts in stable upland sites and the role of bioturbation: a review. *Geoarchaeology*, **17**(1), 41–51.

Berna, F., 2010. Bone alteration and diagenesis. In Artioli, G. (ed.), *Scientific Methods and Cultural Heritage. An Introduction to the Application of Materials Science to Archaeometry and Conservation Science*. Oxford: Oxford University Press, pp. 364–367.

Berna, F., and Goldberg, P., 2008. Assessing Paleolithic pyrotechnology and associated hominin behavior in Israel. *Israel Journal of Earth Sciences*, **56**, 107–121.

Berna, F., Behar, A., Shahack-Gross, R., Berg, J., Boaretto, E., Gilboa, A., Sharon, I., Shalev, S., Shilstein, S., Yahalom-Mack, N., Zorn, J. R., and Weiner, S., 2007. Sediments exposed to high temperatures: reconstructing pyrotechnological processes in Late Bronze and Iron Age strata at Tel Dor (Israel). *Journal of Archaeological Science*, **34**(3), 358–373.

Berna, F., Goldberg, P., Horwitz, L. K., Brink, J., Holt, S., Bamford, M., and Chazan, M., 2012. Microstratigraphic evidence of in situ fire in the Acheulean strata of Wonderwerk Cave, Northern Cape Province, South Africa. *Proceedings of the National Academy of Sciences*, **109**(20), E1215–E1220.

Bertran, P., 1993. Deformation-induced microstructure in soils affected by mass movements. *Earth Surface Processes and Landforms*, **18**(7), 645–660.

Bertran, P., 1994. Dégradation des niveaux d'occupation paléolithiques en contexte périglaciaire: Exemples des implications archéologiques. *Paléo*, **6**(1), 285–302.

Bettis, E. A., III, and Mandel, R. D., 2002a. The effects of temporal and spatial patterns of Holocene erosion and alluviation on the archaeological record of the central and eastern Great Plains, U.S.A. *Geoarchaeology*, **17**(2), 141–154.

Bettis, E. A., III, and Mandel, R. D., 2002b. Geomorphology and geoarchaeology. In Benn, D. W. (ed.), *Archaeology in the Eisele's Hill Locality: Phase III Data Recovery Excavations at 13MC134, U.S. Highway 61, Muscatine County, Iowa*. Cresco: Bear Creek Archaeology. BCA Report No. 628/629, pp. 6–16.

Bobrowsky, P. T., Catto, N. R., Brink, J. W., Spurling, B. E., Gibson, T. H., and Rutter, N. W., 1990. Archaeological geology of sites in western and northwestern Canada. In Laska, N. P., and Donahue, J. (eds.), *Archaeological Geology of North America*. Boulder: The Geological Society of America. GSA Centennial, Vol. 4, pp. 87–122.

Bocek, B., 1986. Rodent ecology and burrowing behavior: predicted effects on archaeological site formation. *American Antiquity*, **51**(3), 589–603.

Bonifay, E., 1956. Les sédiments détritiques grossiers dans le remplissage des grottes. Méthode d'étude morphologique et statistique. *L' Anthropologie*, **60**(5–6), 447–461.

Bordes, F., 1954. *Les limons quaternaires du Bassin de la Seine, stratigraphie et archéologie paléolithique*. Paris: Masson.

Bordes, F., 1972. *A Tale of Two Caves*. New York: Harper and Row.

Bowers, P. M., Bonnichsen, R., and Hoch, D. M., 1983. Flake dispersal experiments: noncultural transformation of the archaeological record. *American Antiquity*, **48**(3), 553–572.

Bryan, K., and Ray, L. L., 1940. *Geologic Antiquity of the Lindenmeier Site in Colorado*. Washington, DC: Smithsonian Institution. Smithsonian Miscellaneous Collections 99, Vol. 2.

Butzer, K. W., 1982. *Archaeology as Human Ecology: Method and Theory for a Contextual Approach*. Cambridge: Cambridge University Press.

Cameron, D., White, P., Lampert, R., and Florek, S., 1990. Blowing in the wind. Site destruction and site creation at Hawker Lagoon, South Australia. *Australian Archaeology*, **30**, 58–69.

Canti, M. G., 2003. Earthworm activity and archaeological stratigraphy: a review of products and processes. *Journal of Archaeological Science*, **30**(2), 135–148.

Cornwall, I. W., 1953. *Soils for the Archaeologist*. New York: Macmillan.

Courty, M. A., Goldberg, P., and Macphail, R. I., 1989. *Soils and Micromorphology in Archaeology*. Cambridge: Cambridge University Press.

Darwin, C., 1881. *The Formation of Vegetable Mould through the Action of Worms, with Observations on Their Habits*. London: John Murray.

Dean, M., Ferrari, B., Oxley, I., Redknap, M., and Watson, K. (eds.), 1992. *Archaeology Underwater: The NAS Guide to Principles and Practice*. Dorchester: Nautical Archaeology Society.

Dibble, D. S., and Lorrain, D., 1968. *Bonfire Shelter: A Stratified Bison Kill Site, Val Verde County, Texas. Austin*. Austin: Texas Memorial Museum, University of Texas. Texas Memorial Museum Miscellaneous Paper, Vol. 1.

Dixon, E. J., Heaton, T. H., Fifield, T. E., Hamilton, T. D., Putnam, D. E., and Grady, F., 1997. Late Quaternary regional geoarchaeology of southeast Alaska karst: a progress report. *Geoarchaeology*, **12**(6), 689–712.

Donahue, J., and Adovasio, J. M., 1990. Evolution of sandstone rockshelters in eastern North America: a geoarchaeological perspective. In Lasca, N. P., and Donahue, J. (eds.), *Archaeological Geology of North America*. Boulder: Geological Society of America. GSA Centennial Special, Vol. 4, pp. 231–251.

Duffield, L. F., 1970. Vertisols and their implications for archaeological research. *American Anthropologist*, **72**(5), 1055–1062.

Erlandson, J. M., 1993. Evidence for a Pleistocene human occupation of Daisy Cave, San Miguel Island, California. *Current Research in the Pleistocene*, **10**, 17–21.

Faught, M. K., 2002–2004. Submerged Paleoindian and Archaic sites of the Big Bend, Florida. *Journal of Field Archaeology*, 29(3–4): 273–290.

Feathers, J., Kipnis, R., Piló, L., Arroyo-Kalin, M., and Coblentz, D., 2010. How old is Luzia? Luminescence dating and stratigraphic integrity at Lapa Vermelha, Lagoa Santa, Brazil. *Geoarchaeology*, **25**(4), 395–436.

Fedje, D. W., and Christensen, T., 1999. Modeling paleoshorelines and locating early Holocene coastal sites in Haida Gwaii. *American Antiquity*, **64**(4), 635–652.

Fedje, D. W., Wigen, R. J., McClaren, D., and Mackie, Q., 2004. Pre-Holocene archaeology and environment from karst cases in Haida Gwaii, west coast, Canada. Paper presented to the 57th Annual Northwest Anthropological Conference, Eugene.

Feibel, C. S., 2001. Archaeological sediments in lake margin environments. In Stein, J. K., and Farrand, W. R. (eds.), *Sediments in Archaeological Context*. Salt Lake City: The University of Utah Press, pp. 127–148.

Flemming, N. C., 1983. Preliminary geomorphological survey of an Early Neolithic submerged site in the Sporadhes, N. Aegean. In Masters, P. M., and Flemming, N. C. (eds.), *Quaternary Coastlines and Marine Archaeology: Towards the Prehistory of Land Bridges and Continental Shelves*. London: Academic, pp. 233–268.

Fujita, H., and Poyatos de Paz, G., 1998. Settlement patterns on Espíritu Santo Island, Baja California Sur. *Pacific Coast Archaeological Society Quarterly*, **34**(4), 67–105.

Galili, E., and Nir, Y., 1993. The submerged pre-pottery Neolithic water well at Atlit-Yam, northern Israel, and its palaeoenvironmental implications. *The Holocene*, **3**(3), 265–270.

Gibbard, P. L., 1994. *Pleistocene History of the Lower Thames Valley*. Cambridge: Cambridge University Press.

Goebel, T., Graf, K., Hockett, B., and Rhode, D., 2007. The Paleoindian occupations at Bonneville Estates Rockshelter, Danger Cave, and Smith Creek Cave (Eastern Great Basin, U.S.A.): interpreting their radiocarbon chronologies. In Kornfeld, M., Vasil'ev, S., and Miotti, L. (eds.), *On Shelter's Ledge: Histories, Theories and Methods of Rockshelter Research*. Oxford: Archaeopress. BAR International Series 1655, pp. 147–161.

Goldberg, P. 1973. *Sedimentology, Stratigraphy and Paleoclimatology of et-Tabun Cave, Mount Carmel, Israel*. PhD thesis, University of Michigan.

Goldberg, P., 2000. Micromorphology and site formation at Die Kelders Cave 1, South Africa. *Journal of Human Evolution*, **38**(1), 43–90.

Goldberg, P., 2001. Some micromorphological aspects of prehistoric cave deposits. *Cahiers d' archéologie du CELAT*, **10**(série archéométrie 1), 161–175.

Goldberg, P., and Bar-Yosef, O., 1998. Site formation processes in Kebara and Hayonim Caves and their significance in Levantine prehistoric caves. In Akazawa, T., Aoki, K., and Bar-Yosef, O. (eds.), *Neandertals and Modern Humans in Western Asia*. New York: Plenum, pp. 107–125.

Goldberg, P., and Berna, F., 2010. Micromorphology and context. *Quaternary International*, **214**(1–2), 56–62.

Goldberg, P., and Macphail, R. I., 2006. *Practical and Theoretical Geoarchaeology*. Oxford: Blackwell.

Goldberg, P., and Macphail, R. I., 2008. Formation processes. In Pearsall, D. M. (ed.), *Encyclopedia of Archaeology*. New York: Academic, Vol. 3, pp. 2013–2017.

Goldberg, P., and Macphail, R. I., 2012. Gorham's cave sediment micromorphology. In Barton, R. N. E., Stringer, C. B., and Finlayson, J. C. (eds.), *Neanderthals in Context*. Oxford: Oxbow Books, pp. 50–61.

Goldberg, P., and Mandel, R. D., 2008. Caves and rockshelters. In Pearsall, D. M. (ed.), *Encyclopedia of Archaeology*. New York: Academic, Vol. 2, pp. 966–974.

Goldberg, P., and Sherwood, S. C., 2006. Deciphering human prehistory through the geoarchaeological study of cave sediments. *Evolutionary Anthropology*, **15**(1), 20–36.

Goldberg, P., Weiner, S., Bar-Yosef, O., Xu, Q., and Liu, J., 2001. Site formation processes at Zhoukoudian, China. *Journal of Human Evolution*, **41**(5), 483–530.

Goldberg, P., Laville, H., Meignen, L., and Bar-Yosef, O., 2007. Stratigraphy and geoarchaeological history of Kebara Cave, Mount Carmel. In Bar-Yosef, O., and Meignen, L. (eds.), *Kebara Cave, Mount Carmel, Israel: The Middle and Upper Paleolithic Archaeology, Part 1*. Cambridge, MA: Peabody Museum, Harvard University. American School of Prehistoric Research Bulletin 49, pp. 49–89.

Goldberg, P., Miller, C. E., Schiegl, S., Ligouis, B., Berna, F., Conard, N. J., and Wadley, L., 2009. Bedding, hearths, and site maintenance in the Middle Stone Age of Sibudu Cave, KwaZulu-Natal, South Africa. *Archaeological and Anthropological Sciences*, **1**(2), 95–122.

Goldberg, P., Dibble, H., Berna, F., Sandgathe, D., McPherron, S. J. P., and Turq, A., 2012. New evidence on Neandertal use of fire: examples from Roc de Marsal and Pech de l'Azé IV. *Quaternary International*, **247**, 325–340.

Goldberg, P., Berna, F., and Chazan, M., 2015. Deposition and diagenesis in the earlier Stone Age of Wonderwerk Cave, Excavation 1, South Africa. *African Archaeological Review (online)*, **32**, 1–29.

Grosman, L., Sharon, G., Goldman-Neuman, T., Smikt, O., and Smilansky, U., 2011. Studying post depositional damage on Acheulian bifaces using 3-D scanning. *Journal of Human Evolution*, **60**(4), 398–406.

Gruhn, R., and Bryan, A. L., 2002. An interim report on two rockshelter sites with Early Holocene occupation in the northern Baja California peninsula. In Wilken-Robertson, M., Santos Mena, M., Castillo Sarabia, M. E., and Laylander, D. (eds.), *II Encuentro binacional "Balances y perspectivas de la antropologia e historia de Baja California": Memorias del simposium 30 noviembre y 1 diciembre 2001, Ensenada, Baja California, Mexico [2nd Binational symposium "Balances and perspectives on the anthropology and history of Baja California": symposium papers, November 30 and December 1, 2001, Ensenada, Baja California, Mexico]*. Ensenada: Instituto de Culturas Nativas de Baja California and Instituto Nacional de Antropología e Historia.

Gusick, A. E., and Faught, M. K., 2011. Prehistoric archaeology underwater: a nascent subdiscipline critical to understanding early coastal occupations and migration routes. In Bicho, N. F., Haws, J. A., and Davis, L. G. (eds.), *Trekking the Shore: Changing Coastlines and the Antiquity of Coastal Settlement*. New York: Springer, pp. 27–50.

Hahn, J., 1988. *Die Geißenklösterle-Höhle im Achtal bei Blaubeuren I. Fundhorizontbildung und Besiedlung im Mittelpaläolithikum und im Aurignacien*. Stuttgart: Kommissionsverg, Korad Theiss Verlag. Forschungen und Berichte zur Vor- und Frühgeschichte in Baden-Württemberg, Band 26.

Haynes, C. V., Jr., and Agogino, G. A., 1966. Prehistoric springs and geochronology of Blackwater No. 1 locality, New Mexico. *American Antiquity*, **31**(6), 812–821.

Hofman, J. L., 1986. Vertical movements of artifacts in alluvial and stratified deposits. *Current Anthropology*, **27**(2), 163–171.

Holliday, V. T., 2004. *Soils in Archaeological Research*. Oxford: Oxford University Press.

Holmes, W. H., 1893. Vestiges of early man in Minnesota. *American Geologist*, **11**(4), 219–240.

Hopkins, D. M., and Giddings, J. L., 1953. *Geological Background of the Iyatayet Archeological Site, Cape Denbigh, Alaska*. Washington, DC: Smithsonian Institution. Smithsonian Miscellaneous Collections 121, Vol. 11.

Horwitz, L. K., and Goldberg, P., 1989. A study of Pleistocene and Holocene hyaena coprolites. *Journal of Archaeological Science*, **16**(1), 71–94.

Inman, D. L., 1983. Application of coastal dynamics to the reconstruction of paleocoastlines in the vicinity of La Jolla, California. In Masters, P. M., and Flemming, N. C. (eds.), *Quaternary Coastlines and Marine Archaeology: Towards the Prehistory of Land Bridges and Continental Shelves*. London: Academic, pp. 1–49.

Jenkins, D. L., 2007. Distribution and dating of cultural and paleontological remains at the Paisley Five Mile Point Caves in the northern Great Basin: an early assessment. In Graf, K. E., and Schmidt, D. N. (eds.), *Paleoindian or Paleoarchaic: Great Basin Human Ecology at the Pleistocene-Holocene Transition*. Salt Lake City: University of Utah Press, pp. 57–81.

Johnson, D. L., 1990. Biomantle evolution and the redistribution of earth materials and artifacts. *Soil Science*, **149**(2), 84–102.

Johnson, D. L., 1992. Biomechanical processes and the Gaia paradigm in a unified pedo-geomorphic and pedo-archaeologic framework: Dynamic denudation. In Foss, J. E., Timpson, M. E., and Morris, M. W. (eds.), *Proceedings of the First International Conference on Pedo-Archaeology, February 16–20, 1992*. Special Publication 93-03. Knoxville: The University of Tennessee Agricultural Experiment Station, pp. 41–67.

Johnson, D. L., 2002. Darwin would be proud: bioturbation, dynamic denudation, and the power of theory in science. *Geoarchaeology*, **17**(1), 7–40.

Johnson, D. L., and Hansen, K. L., 1974. The effects of frost-heaving on objects in soils. *Plains Anthropologist*, **19**(64), 81–98.

Johnson, D. L., and Watson-Stegner, D., 1990. The soil-evolution model as a framework for evaluating pedoturbation in archaeological site formation. In Lasca, N. P., and Donahue, J. (eds.), *Archaeological Geology of North America*. Boulder: The Geological Society of America. GSA Centennial Special volume 4, pp. 541–560.

Johnson, D. L., Muhs, D. R., and Barnhardt, M. L., 1977. The effects of frost heaving on objects in soils, II: laboratory experiments. *Plains Anthropologist*, **22**(76), 133–147.

Johnson, D. L., Domier, J. E. J., and Johnson, D. N., 2005. Reflections on the nature of soil and its biomantle. *Annals of the Association of American Geographers*, **95**(1), 11–31.

Jordá Pardo, J. F., Baena Preysler, J., Carral González, P., García-Guinea, J., Correcher Delgado, V., and Yravedra Sáinz de los Terreros, J., 2008. Procesos sedimentarios y diagenéticos en el registro arqueológico del yacimiento pleistoceno de la cueva de el Esquilleu (Picos de Europa, norte de España). *Revista Cuaternario y Geomorfología*, **22**(3–4), 31–46.

Karkanas, P., and Goldberg, P., 2007. Micromorphology of sediments: deciphering archaeological context. *Israel Journal of Earth Science*, **56**, 63–71.

Karkanas, P., and Goldberg, P., 2010. Site formation processes at Pinnacle Point Cave 13B (Mossel Bay, Western Cape Province, South Africa): resolving stratigraphic and depositional complexities with micromorphology. *Journal of Human Evolution*, **59** (3–4), 256–273.

Karkanas, P., Bar-Yosef, O., Goldberg, P., and Weiner, S., 2000. Diagenesis in prehistoric caves: the use of minerals that form *in situ* to assess the completeness of the archaeological record. *Journal of Archaeological Science*, **27**(10), 915–929.

Karkanas, P., Shahack-Gross, R., Ayalon, A., Bar-Matthews, M., Barkai, R., Frumkin, A., Gopher, A., and Stiner, M. C., 2007. Evidence for habitual use of fire at the end of the lower paleolithic: site-formation processes at Qesem Cave, Israel. *Journal of Human Evolution*, **53**(2), 197–212.

Laville, H. 1964. Recherches sédimentologiques sur la paléoclimatologie du Würm récent en Périgord. PhD thesis, Université de Bordeaux.
Laville, H., Rigaud, J.-P., and Sackett, J., 1980. *Rock Shelters of the Perigord: Geological Stratigraphy and Archaeological Succession*. New York: Academic.
Leigh, D. S., 2001. Buried artifacts in sandy soils: techniques for evaluating pedoturbation versus sedimentation. In Goldberg, P., Holliday, V. T., and Ferring, C. R. (eds.), *Earth Sciences and Archaeology*. New York: Kluwer/Plenum, pp. 269–293.
Macphail, R. I., and Goldberg, P., 1990. The micromorphology of tree subsoil hollows: their significance to soil science and archaeology. In Douglas, L. A. (ed.), *Soil Micromorphology: A Basic and Applied Science*. Amsterdam: Elsevier. Developments in Soil Science 19, pp. 425–429.
Mallol, C., Cabanes, D., and Baena, J., 2010. Microstratigraphy and diagenesis at the upper Pleistocene site of Esquilleu Cave (Cantabria, Spain). *Quaternary International*, **214**(1–2), 70–81.
Mandel, R. D., 1995. Geomorphic controls of the Archaic record in the Central Plains of the United States. In Bettis, E. A., III (ed.), *Archaeological Geology of the Archaic Period in North America*. Boulder: The Geological Society of America. Geological Society of America Special Paper 297, pp. 37–66.
Mandel, R. D., 2006. The effects of late Quaternary landscape evolution on the archaeology of Kansas. In Hoard, R. J., and Banks, W. E. (eds.), *Kansas Archaeology*. Lawrence: University Press of Kansas, pp. 46–75.
Mandel, R. D., and Goldberg, P., 2011. Geoarchaeology and paleoenvironmental context. In Haas, J. R. (ed.), *Phase III Mitigation for Archaeological Site 32RY473, Ramsey County, North Dakota*. Milwaukee: Great Lakes Archaeological Research Center. Report of Investigations, Vol. 774, pp. 37–63.
Mandel, R. D., and Simmons, A. H., 1997. Geoarchaeology of the Akrotiri *Aetokremnos* rockshelter, Cyprus. *Geoarchaeology*, **12**(6), 567–605.
Mandel, R. D., and Simmons, A. H., 2001. Prehistoric occupation of late quaternary landscapes near Kharga Oasis, Western Desert of Egypt. *Geoarchaeology*, **16**(1), 95–117.
Mandel, R. D., Murphy, L. R., and Mitchell, M. D., 2014. Geoarchaeology and paleoenvironmental context of the Beacon Island site, an Agate Basin (Paleoindian) bison kill in northwestern North Dakota, USA. *Quaternary International*, **342**, 91–113.
Marean, C. W., Goldberg, P., Avery, G., Grine, F. E., and Klein, R. G., 2000. Middle Stone Age stratigraphy and excavations at Die Kelders Cave 1 (Western Cape Province, South Africa): the 1992, 1993, and 1995 field seasons. *Journal of Human Evolution*, **38**(1), 7–42.
Marean, C. W., Bar-Matthews, M., Fisher, E., Goldberg, P., Herries, A., Karkanas, P., Nilssen, P. J., and Thompson, E., 2010. The stratigraphy of the Middle Stone Age sediments at Pinnacle Point Cave 13B (Mossel Bay, Western Cape Province, South Africa). *Journal of Human Evolution*, **59**(3–4), 234–255.
Mayer, J. H., 2002. Evaluating natural site formation processes in eolian dune sands: a case study from the Krmpotich Folsom site, Killpecker Dunes, Wyoming. *Journal of Archaeological Science*, **29**(10), 1199–1211.
McFadgen, B. G., 2007. *Hostile Shores: Catastrophic Events in Prehistoric New Zealand and Their Impact on Maori Coastal Communities*. Auckland: Auckland University Press.
Meignen, L., Goldberg, P., and Bar-Yosef, O., 2007. The hearths at Kebara Cave and their role in site formation processes. In Bar-Yosef, O., and Meignen, L. (eds.), *Kebara Cave, Mount Carmel, Israel: The Middle and Upper Paleolithic Archaeology, Part 1*. Cambridge, MA: Peabody Museum, Harvard University. American School of Prehistoric Research Bulletin 49, pp. 91–122.
Mentzer, S. M., and Quade, J., 2013. Compositional and isotopic analytical methods in archaeological micromorphology. *Geoarchaeology*, **28**(1), 87–97.
Michie, J., 1990. Bioturbation and gravity as a potential site formation process: the open area site, 38GE261, Georgetown County, South Carolina. *South Carolina Antiquities*, **22**, 27–46.
Miller, C. E., Conard, N. J., Goldberg, P., and Berna, F., 2010. Dumping, sweeping and trampling: experimental micromorphological analysis of anthropogenically modified combustion features. *P@lethnologie*, **2**, 25–37. http://www.palethnologie.org
Miller, C. E., Goldberg, P., and Berna, F., 2013. Geoarchaeological investigations at Diepkloof Rock Shelter, Western Cape, South Africa. *Journal of Archaeological Science*, **40**(9), 3432–3452.
Minor, R., and Grant, W. C., 1996. Earthquake-induced subsidence and burial of late Holocene archaeological sites, northern Oregon coast. *American Antiquity*, **61**(4), 772–781.
Moody, U. L., and Dort, W., Jr., 1990. Microstratigraphic analysis of sediments and soils: Wasden archaeological site, eastern Snake River Plains, Idaho. In Lasca, N. P., and Donahue, J. (eds.), *Archaeological Geology of North America*. Boulder: The Geological Society of America. GSA Centennial Special, Vol. 4, pp. 361–382.
Morris, M. W., Ammons, J. T., and Santas, P., 1997. Evidence for subsurface translocation of ceramic artifacts in a Vertisol in eastern Crete, Greece. In Goodyear, A. C., Foss, J. E., and Sassaman, K. E. (eds.), *Proceedings of the Second International Conference on Pedo-Archaeology*. Columbia: South Carolina Institute of Archaeology and Anthropology, University of South Carolina. Anthropological Studies 10. Occasional Papers, South Carolina Institute of Archaeology and Anthropology, pp. 41–51.
Muckelroy, K., 1978. *Maritime Archaeology*. Cambridge: Cambridge University Press.
Muhs, D. R., 1987. Geomorphic processes in the Pacific coast and mountain system of central and southern California. In Graf, W. L. (ed.), *Geomorphic Systems of North America*. Boulder: Geological Society of America. GSA Centennial Special volume 2, pp. 560–570.
Ohel, M. Y., 1987. More on the effects of burrowing animals on archaeological site formation. *American Antiquity*, **52**(4), 856–857.
Overstreet, D. F., and Kolb, M. F., 2003. Geoarchaeological contexts for Late Pleistocene archaeological sites with human-modified woolly mammoth remains in southeastern Wisconsin, U.S.A. *Geoarchaeology*, **18**(1), 91–114.
Peacock, E., and Fant, D. W., 2002. Biomantle formation and artifact translocation in upland sandy soils: an example from the Holly Springs National Forest, north-central Mississippi, U.S. A. *Geoarchaeology*, **17**(1), 91–114.
Petraglia, M. D., and Nash, D. T., 1987. The impact of fluvial processes on experimental sites. In Nash, D. T., and Petraglia, M. D. (eds.), *Natural Formation Processes and the Archaeological Record*. Oxford: British Archaeological Reports. British Archaeological Reports, International Series 352, pp. 108–130.
Pietsch, D., 2013. Krotovinas – soil archives of steppe landscape history. *Catena*, **104**, 257–264.
Rapp, G. R., and Hill, C. L., 1998. *Geoarchaeology: The Earth Science Approach to Archaeological Interpretation*. New Haven: Yale University Press.
Rapp, G. R., and Hill, C. L., 2006. *Geoarchaeology: The Earth Science Approach to Archaeological Interpretation*, 2nd edn. New Haven: Yale University Press.
Reinhardt, G. A., 1993. Hydrologic artifact dispersals at Pingasagruk, North Coast, Alaska. *Geoarchaeology*, **8**(6), 493–513.
Rhode, D., Goebel, T., Graf, K. E., Hockett, B. S., Jones, K. T., Madsen, D. B., Oviatt, C. G., and Schmitt, D. N., 2005. Latest Pleistocene-early Holocene human occupation and

paleoenvironmental change in the Bonneville Basin, Utah-Nevada. In Pederson, J. L., and Dehler, C. M. (eds.), *Interior Western United States*. Boulder: Geological Society of America. GSA Field Guide 6, pp. 211–230.

Rick, T. C., Erlandson, J. M., and Vellanoweth, R. L., 2006. Taphonomy and site formation on California's Channel Islands. *Geoarchaeology*, **21**(6), 567–589.

Roe, D., 1993. Landmark sites of the British Paleolithic. *Review of Archaeology*, **14**(2), 1–9.

Rolfsen, P., 1980. Disturbance of archaeological layers by processes in the soils. *Norwegian Archaeological Review*, **13**(2), 110–118.

Schaetzl, R. J., and Thompson, M. L., 2015. *Soils: Genesis and Geomorphology*, 2nd edn. New York: Cambridge University Press.

Schaetzl, R. J., Burns, S. F., Small, T. W., and Johnson, D. L., 1990. Tree uprooting: review of types and patterns of soil disturbance. *Physical Geography*, **11**(3), 277–291.

Schick, K. D., 1987. Experimentally-derived criteria for assessing hydrologic disturbance of archaeological sites. In Nash, D. T., and Petraglia, M. D. (eds.), *Natural Formation Processes and the Archaeological Record*. Oxford: British Archaeological Reports. British Archaeological Reports, International Series 352, pp. 86–107.

Schiegl, S., and Conard, N. J., 2006. The Middle Stone Age sediments at Sibudu: results from FTIR spectroscopy and microscopic analyses. *Southern African Humanities*, **18**(1), 149–172.

Schiegl, S., Goldberg, P., Pfretzschner, H.-U., and Conard, N. J., 2003. Paleolithic burnt bone horizons from the Swabian Jura: distinguishing between *in situ* fire places and dumping areas. *Geoarchaeology*, **18**(5), 541–565.

Schiffer, M. B., 1972. Archaeological context and systemic context. *American Antiquity*, **37**(2), 156–165.

Schiffer, M. B., 1987. *Formation Processes of the Archaeological Record*. Albuquerque: University of New Mexico Press.

Schild, R. A., and Wendorf, F. A., 1975. New explorations in the Egyptian Sahara. In Wendorf, F. A., and Marks, A. E. (eds.), *Problems in Prehistory*. Dallas: Southern Methodist University Press, pp. 65–112.

Schweger, C., 1985. Geoarchaeology of northern regions: lessons from cryoturbation at Onion Portage, Alaska. In Stein, J. K., and Farrand, W. R. (eds.), *Archaeological Sediments in Context*. Orono: Center for the Study of Early Man, University of Maine. Peopling of the Americas Edited Volume Series 1, pp. 127–141.

Sellards, E. H., 1917. Further notes on human remains from Vero, Florida. *American Anthropologist*, **19**(2), 239–251.

Sellards, E. H., 1938. Artifacts associated with fossil elephant. *Geological Society of America Bulletin*, **49**(7), 999–1010.

Shahack-Gross, R., Berna, F., Karkanas, P., and Weiner, S., 2004. Bat guano and preservation of archaeological remains in cave sites. *Journal of Archaeological Science*, **31**(9), 1259–1272.

Shaler, N. S., 1891. The origin and nature of soils. *U. S. Geological Survey 12th Annual Report 1890–1891, Part 1.* Washington, DC: U.S. Geological Survey, pp. 213–345.

Shelley, P. H., and Nials, F. L., 1983. A preliminary evaluation of aeolian processes in artifact dislocation and modification: an experimental approach to one depositional environment. *Proceedings of the New Mexico Archaeological Council*, **5**, 50–56.

Sherwood, S. C., and Goldberg, P., 2001. A geoarchaeological framework for the study of karstic cave sites in the eastern woodlands. *Midcontinental Journal of Archaeology*, **26**(2), 145–167.

Sherwood, S. C., Driskell, B. N., Randall, A. R., and Meeks, S. C., 2004. Chronology and stratigraphy at Dust Cave, Alabama. *American Antiquity*, **69**(3), 533–554.

Simms, S. R., 1984. Experiments on artifact movement in sand dunes. Archaeological excavations in the Sevier and Escalante Deserts, western Utah. In Simms, S. R., and Isgreen, M. C. (eds.), *Archaeological Center Reports of Investigations 83–12*. Salt Lake City: University of Utah, pp. 377–388.

Skaarup, J., and Grøn, O., 2004. *Møllegabet II: A Submerged Mesolithic Settlement in Southern Denmark*. Oxford: Archaeopress. British Archaeological Reports, International Series 1328.

Soil Survey Staff, 2014. *Keys to Soil Taxonomy*, 12th edn. Washington, DC: US Department of Agriculture, Natural Resources Conservation Service.

Speth, J. D., Meignen, L., Bar-Yosef, O., and Goldberg, P., 2012. Spatial organization of Middle Paleolithic occupation X in Kebara Cave (Israel): concentrations of animal bones. *Quaternary International*, **247**, 85–102.

Stein, J. K., 1983. Earthworm activity: a source of potential disturbance of archaeological sediments. *American Antiquity*, **48**(2), 277–289.

Stewart, D. J., 1999. Formation processes affecting submerged archaeological sites: an overview. *Geoarchaeology*, **14**(6), 565–587.

Stright, M. J., 1995. Archaic period sites on the continental shelf of North America: the effect of relative sea-level changes on archaeological site locations and preservation. In Bettis, E. A., III (ed.), *Archaeological Geology of the Archaic Period in North America*. Boulder: Geological Society of America. GSA Special Paper 297, pp. 131–148.

Tankard, A. J., and Schweitzer, F. R., 1974. The geology of Die Kelders Cave and environs: a palaeoenvironmental study. *South African Journal of Science*, **70**(12), 365–369.

Tankersley, K. B., 1997. Sheriden: a Clovis cave site in eastern North America. *Geoarchaeology*, **12**(6), 713–724.

Thoms, A. V., 2007. Excavation areas and site-formation contexts. In Thoms, A. V., and Mandel, R. D. (eds.), *Archaeological and Paleoecological Investigations at the Richard Beene Site, South-Central Texas*. College Station: Center for Ecological Archaeology, Texas A&M University. Reports of Investigations 8, pp. 61–85.

Thorson, R. M., 1990. Geologic contexts of archaeological sites in Beringia. In Laska, N. P., and Donahue, J. (eds.), *Archaeological Geology of North America*. Boulder: The Geological Society of America. GSA Centennial, Vol. 4, pp. 399–420.

Thorson, R. M., and Hamilton, T. D., 1977. Geology of the Dry Creek site: a stratified early man site in interior Alaska. *Quaternary Research*, **7**(2), 149–176.

Turq, A., Dibble, H. L., Goldberg, P., McPherron, S. P., Sandgathe, D., Jones, H., Maddison, K., Maureille, B., Mentzer, S., Rink, J., and Steenhuyse, A., 2011. Les Fouilles Récentes du Pech de l'Azé IV (Dordogne). *Gallia Préhistoire*, **53**, 1–58.

Vallverdú, J., Alonso, S., Bargalló, A., Bartrolí, R., Campeny, G., Carrancho, Á., Expósito, I., Fontanals, M., Gabucio, J., Gómez, B., Prats, J. M., Sañudo, P., Solé, À., Vilalta, J., and Carbonell, E., 2012. Combustion structures of archaeological level O and mousterian activity areas with use of fire at the Abric Romaní rockshelter (NE Iberian Peninsula). *Quaternary International*, **247**, 313–324.

Van Nest, J., 2002. The good earthworm: how natural processes preserve upland Archaic archaeological sites of western Illinois, U.S.A. *Geoarchaeology*, **17**(1), 53–90.

Van Vliet-Lanoë, B., 1985. Frost effects in soils. In Boardman, J. (ed.), *Soils and Quaternary Landscape Evolution*. Chichester: Wiley, pp. 117–158.

Van Vliet-Lanoë, B., 1998. Frost and soils: implications for paleosols, paleoclimates and stratigraphy. *Catena*, **34**(1–2), 157–183.

Villa, P., 1982. Conjoinable pieces and site formation processes. *American Antiquity*, **47**(2), 276–290.

Wadley, L., Sievers, C., Bamford, M., Goldberg, P., Berna, F., and Miller, C., 2011. Middle Stone Age bedding construction and settlement patterns at Sibudu, South Africa. *Science*, **334**(6061), 1388–1391.

Wandsnider, L., 1988. Experimental investigation of the effect of dune processes on archaeological remains. *American Archeology*, **7**(1), 18–29.
Waters, M. R., 1992. *Principles of Geoarchaeology: A North American Perspective*. Tucson: University of Arizona Press.
Weiner, S., 2010. *Microarchaeology: Beyond the Visible Archaeological Record*. New York: Cambridge University Press.
Weiner, S., Goldberg, P., and Bar-Yosef, O., 2002. Three-dimensional distribution of minerals in the sediments of Hayonim Cave, Israel: diagenetic processes and archaeological implications. *Journal of Archaeological Science*, **29**(11), 1289–1308.
Weiner, S., Berna, F., Cohen-Ofri, I., Shahack-Gross, R., Albert, R. M., Karkanas, P., Meignen, L., and Bar-Yosef, O., 2007. Mineral distributions in Kebara Cave: diagenesis and its effect on the archaeological record. In Bar-Yosef, O., and Meignen, L. (eds.), *Kebara Cave, Mount Carmel, Israel: The Middle and Upper Paleolithic Archaeology, Part 1*. Cambridge, MA: Peabody Museum, Harvard University. American School of Prehistoric Research Bulletin 49, pp. 131–146.
Wells, L. E., 2001. Archaeological sediments in coastal environments. In Stein, J. K., and Farrand, W. R. (eds.), *Sediments in Archaeological Context*. Salt Lake City: University of Utah Press, pp. 149–181.
Wendorf, F. A., and Schild, R. A., 1980. *Prehistory of the Eastern Sahara*. New York: Academic.
Werz, B. E. J. S., and Flemming, N. C., 2001. Discovery in Table Bay of the oldest handaxes yet found underwater demonstrates preservation of hominid artefacts on the continental shelf. *South African Journal of Science*, **97**(5–6), 183–185.
West, R. G., Gibbard, P. L., Boreham, S., and Rolfe, C., 2014. Geology and geomorphology of the Palaeolithic site at High Lodge, Mildenhall, Suffolk, England. *Proceeding of the Yorkshire Geological Society*, **60**, 99–121.
White, P. S., 1979. Pattern, process, and natural disturbance in vegetation. *The Botanical Review*, **45**(3), 229–299.
Wilson, M. C., 1990. Archaeological geology in western Canada: techniques, approaches, and integrative themes. In Laska, N. P., and Donahue, J. (eds.), *Archaeological Geology of North America*. Boulder: The Geological Society of America. GSA Centennial, Vol. 4, pp. 61–86.
Wood, W. R., and Johnson, D. L., 1978. A survey of disturbance processes in archaeological site formation. *Advances in Archaeological Method and Theory*, **1**, 315–381.
Woodward, J. C., and Goldberg, P., 2001. The sedimentary records in Mediterranean rockshelters and caves: archives of environmental change. *Geoarchaeology*, **16**(4), 327–354.
Zeuner, F. E., 1946. *Dating the Past: An Introduction to Geochronology*. London: Methuen.

Cross-references

Alluvial Settings
Cave Settings
Coastal Settings
Colluvial Settings
Eolian Settings: Loess
Eolian Settings: Sand
Fourier Transform Infrared Spectroscopy (FTIR)
Glacial Settings
Mass Movement
Paleoenvironmental Reconstruction
Rockshelter Settings
Scanning Electron Microscopy (SEM)
Shipwreck Geoarchaeology
Soil Micromorphology
Tsunamis
X-ray Fluorescence (XRF) Spectrometry in Geoarchaeology

SITE PRESERVATION

Henk Kars
Geo- and Bioarchaeology, Faculty of Earth and Life Sciences, VU University, Amsterdam, The Netherlands

Definition

In situ preservation of archaeological heritage means the preservation of sites and remains in their original location within the burial environment, with the purpose of leaving archaeological sites intact, authentic, and as undamaged as possible. This is contrary to archaeological excavation, which can be seen as preservation ex situ.

Introduction

Subsumed within the idea of cultural heritage are structures, constructions, groups of buildings, developed sites, moveable objects, monuments of other kinds, as well as the context of all the aforementioned, whether situated on land or under water. This proposition was stated in the European Valletta Convention of 1992 (or the revised European Convention on the Protection of the Archaeological Heritage) as well as in the World Heritage Convention of UNESCO, which also includes natural heritage. For many years, there has been an awareness of the importance of preserving ancient monumental buildings; however, most of our archaeological heritage, reflecting many significant human activities of the past, is invisibly hidden in the soil. Archaeological resource managers realized several decades ago that preserving archaeological remains underground rather than excavating them should be the main policy in order to protect them for future generations. This policy of sustainable site preservation or preservation in situ using the burial environment as a storeroom has become a challenging research subject for geoarchaeologists. Nevertheless, in situ preservation is not always the best choice. Excavations can be conducted in order to make a significant contribution to our knowledge of the past, and this should be the case when the archaeological remains in question are threatened by any human or natural agency, such as urban developments, erosion, and changing environmental conditions. Sometimes, in situ preservation and excavation can be combined for optimum outcomes (see Figure 1).

Background

Recent developments in archaeological resource management have had a tremendous impact on perspectives regarding the sustainable protection and development of our archaeological resources. The archaeological record that lies beneath the ground surface – encompassing artifacts, sites, and former landscapes – is now seen as a resource for present and future generations rather than a static fabric of the past. This view is based on the rationale that research questions might evolve over time due to changing paradigms and that research methods will

Site Preservation, Figure 1 Sometimes excavation and site preservation are combined. The photograph shows a partially preserved burial mound. The open parts were excavated, while the remaining parts are protected and remain available for future investigations (Photo: Dutch Archaeological Monument Watch, 2007).

most certainly improve, including numerous technological advancements of the past few decades described in this volume as obvious examples. With changing questions and techniques, new excavations would need to be conducted on similar archaeological remains to reexamine old conclusions in the context of fresh ideas and capabilities. This also implies that archaeological sites will be preserved by inclusion within development schemes and not simply excavated as a quick solution to clearing the land for improvements. Both scientists and policy makers in the field realize that this proactive approach to heritage management must deal with several gaps in our knowledge. One major knowledge gap, for example, is how to preserve artifacts, sites, and landscapes within the burial environment when we understand that nearby land modifications or natural processes might over time affect soil parameters and impose secondary impacts on buried remains.

It is perhaps safe to assume that more than 95 % of the archaeological record worldwide is hidden in the soil and therefore invisible to the untrained eye. This means that, in terms of its perception by the general public, the cultural value of this archaeological record is close to zero. A convincing argument to the public might establish the value of preservation as a mostly intrinsic quality reflecting a potential source of knowledge about our past. How can the information present in features and artifacts within the soil tell us something about early people and former societies? These intrinsic qualities are first determined by the age and character of a site; however, the state of preservation of a site, i.e., how much of the original remains are intact or sufficiently undamaged, is the limiting condition with regard to the amount and clarity of information that can be retrieved from them. Sound and reliable knowledge of degradation mechanisms in relation to soil parameters is therefore essential in the decision-making process regarding the decision over excavation today versus in situ preservation. Yet, an informed decision requires material science specialists as well as experts in the fields of soil science, hydrology, geochemistry, and biogeochemistry.

An archaeological site and the burial environment

The site

With regard to the preservation of archaeological site contents, the first and major concern is the presence of artifacts made of vulnerable materials, like iron, bronze, glass, wood, leather, and bone, and of faunal remains, including human bones. Such remains are most likely to be adversely affected by changing burial conditions. Equally important to the archaeologist are the features in the soil that represent postholes, graves, ditches, storage pits, and extended cultural layers or earthworks. These anthropogenic soils provide much information pertaining to the type of site, its internal structure, and its relationship to the surroundings. These soils can be recognized and separated from natural soils by noting structural and textural differences and by determining their differing compositions, such as increased organic matter or oxides of iron and manganese, which are apparent in color variations compared to natural soils adjacent to the anthropogenic feature.

It is clear that a successful site preservation policy requires sustainable preservation of these anthropogenic soil features in addition to the artifacts and structures found in the site. Therefore, gaining insight into the depositional and postdepositional processes that have formed an archaeological site and preserved it up to the present is an important issue in site preservation studies. Effects of recent and future changes in soil conditions within the burial environment must also be understood. It is important to note that an archaeological site or landscape has to be considered an accumulation of physicochemical and biochemical metastable equilibria in artifact-soil systems, governed by many materials science and soil science parameters, and that these equilibria are critical to achieving sustainable site preservation. This insight is essential to provide decision makers with a risk assessment.

The burial environment

The basic approach in determining and measuring degradation processes in archaeological sites is to characterize their burial environment. By measuring specific soil parameters, degradation processes that might occur in the archaeological materials can be determined. Organic matter is the most reactive solid component in anthropogenic and other soils. The presence or absence of organic matter determines the impact of oxygen and other oxidizing substances (such as iron and manganese oxides, sulfate, and nitrate) on degradation processes, whether reducing conditions or pyrite formation occurs and whether oxygen can penetrate to the buried archaeological materials. Transport of water and reactive components is determined by the geohydrological setting and by the bulk density and porosity of the soil. Another important factor is the presence or absence of lime, which buffers the soil against increased acidity (low pH).

The advantage of this approach is that measurements can be taken relatively simply and with little or no damage to the archaeological site. An important drawback, however, is that these measurements do not provide direct information about what is happening to the archaeological material, nor do they measure active degradation in a particular situation. An additional problem is that very little is known about the rate of the degradation reactions impacting different archaeological materials in the ground. Deducing how rapidly such processes are likely to happen from the moment the burial environment changes and how severe the impact will be is not an easy matter. Therefore, a risk assessment of the site has to be assembled in order to develop a well-defined and cost-effective monitoring plan that will help to maintain the site in its present condition.

Monitoring

The first step in any monitoring plan is to gather information on the properties of the burial environment in relation to the archaeological contents of a site. This is needed for a balanced decision as to what cost-effective measuring methods should be applied and how frequently data should be collected. First, the contents of an archaeological site must be assessed in terms of the kinds of material represented, including especially the presence or absence of extremely vulnerable botanical remains, bone, and inorganics such as metal and glass. Second, the burial environment should be defined, which requires at least information on soil type, parent material, grain size, and organic matter content. In addition to this, the hydrological situation at the site should be described in terms of variations in groundwater level, seepage, drainage, or infiltration and the presence or absence of salt water.

Important soil parameters such as oxygen content and pH, which influence the preservation of archaeological materials, are governed by the dynamics of groundwater and the distribution of soil moisture. Knowledge of the present and likely future behavior of soil moisture at a site is therefore essential.

For many archaeological materials, the presence of oxygen is the key factor controlling degradation. Oxygen causes corrosion, and it is essential for biodegradation by aerobic microorganisms. With regard to the role of oxygen in the degradation of archaeomaterials in soils, a distinction should be made in soil moisture between the unsaturated and saturated zone. It is generally assumed that archaeological materials remain intact in the saturated zone, which is mainly true for areas with stagnating groundwater where the limited oxygen supports anaerobic microorganisms, which inflict minimal destruction. However, in areas with infiltration or seepage of oxygen-bearing groundwater, degradation gradually continues. In the unsaturated zone, empty pore spaces permit oxygen to penetrate directly into the soil, and thus it is available to fuel chemical and biological degradation.

This degradation involves redox reactions, with the transfer of electrons from an oxidizing agent (e.g., oxygen) to a reducing agent such as organic matter, which is present in almost any archaeological site. In addition to measuring the groundwater table, the use of redox probes is a common component of a monitoring program in order to gain insight into the activity of oxygen.

Additional methods can be integrated into the monitoring plan when needed. An example would be the use of micromorphology for gaining insight into the oxidation state of organic matter together with textural changes in the anthropogenic soils. Another example would be the examination of bones to assess their state of preservation not only for morphological study but also for their potential for (stable) isotope and ancient DNA analysis (Figure 2).

In addition to monitoring the preservation state of a site, mitigation measures have to be taken to avoid further degradation in some cases. An example of this is the World Heritage Site of Bryggen in Bergen (Norway), a preserved sector of the old harbor area with houses from as early as the fourteenth century. Monitoring has shown

Site Preservation, Figure 2 Postdepositional processes might have an effect on the usefulness of bone for future bioarchaeological investigations. This section through the root of a medieval human tooth reveals many framboidal pyrite (FeS_2) grains on the surface of the pulp cavity and root canals, and in places, it almost completely fills the root canals. The cementum and dentin of this tooth are stained yellow and orange, indicating infiltration by iron compounds possibly due to oxidation of the pyrite (see Hollund, 2013; Hollund et al., 2013).

damaging settling rates caused by degradation of the archaeological deposits underlying the present-day harbor front of Bryggen. It was established that building activities in the 1970s that erected a modern hotel among other constructions had a dramatic influence on the local groundwater regime, partially draining land beneath the old harbor structures, permitting them to decompose, which in turn initiated compaction of the weakened organic supports and caused them to settle. Infiltration of additional water was needed to stop the degradation of the organic deposits. Examples of solutions that have been designed and implemented include directing shallow infiltration of rainwater from local downpipes and a rainwater garden as a buffer between the upstream urban area and the heritage site (de Beer et al., 2008; Matthiesen, 2008).

Research topics

The current state of knowledge about degradation and preservation of most kinds of archaeological remains, together with an overview of methods for quality assessment of archaeological sites and methodologies for site monitoring, is given in Huisman (2009).

The research community in this field meets at the international Preservation of Archaeological Remains In Situ (PARIS) conferences, which have been held in London (1996, 2001), Amsterdam (2006), Copenhagen (2011), and Kreuzlingen, Switzerland (2015). The aim of these meetings is bringing practitioners (scientists and archaeologists) and stakeholders (cultural resource managers and policy makers) together in order to discuss the latest issues emerging from studies on degradation and monitoring of sites in urban, rural, and marine environments. Based on 20 years of multidisciplinary research, the following four themes can be recognized (Kars and van Heeringen, 2008; Gregory and Matthiesen, 2012):

1. *Degradation of archaeological remains*. Apart from understanding the processes of degradation in archaeological features and objects, can degradation rates under changing conditions be identified and assessed? What rates of deterioration are acceptable before mitigation must be conducted?
2. *Monitoring and mitigation studies*. What kind of monitoring strategies can be developed and for how long should a site be monitored to gain insight into the effects of changing conditions in the environment? Are geotechnical measures available and suitable to slow down processes of decay?
3. *Development of protocols and international standards*. Apart from diverging national legislations and policies, is it possible to develop standards for site monitoring and preservation when sites in relation to their burial environment are so extremely variable?
4. *State of the art of in situ preservation strategies*. Can the effectiveness of in situ preservation research be recognized and documented? Has it led to an improvement of site preservation?

Bibliography

de Beer, H., Christensson, A., and Jensen, J. A., 2008, Bryggen world heritage site: a numerical groundwater model to support archaeological preservation strategies, In Kars, H., and van Heeringen, R. M. (eds.), *Preserving Archaeological Remains In Situ: Proceedings of the 3rd Conference 7–9 December 2006, Amsterdam*. Geoarchaeological and Bioarchaeological Studies 10. Amsterdam: Institute for Geo and Bioarchaeology, VU University, pp. 95–100.

Gregory, D., and Matthiesen H., (eds.), 2012. *Special Issue: Preserving Archaeological Remains In Situ: The 4th International Conference on Preserving Archaeological Remains "in situ" (PARIS4): 23–26 May 2011, the National Museum of Denmark, Copenhagen.* Conservation and Management of Archaeological Sites, **14**(1–4).

Hollund, H. I., 2013. Are teeth better? A histological investigation of diagenesis in a set of archaeological bone-tooth pairs and the implications for sample selection in biomolecular studies. In Hollund, H. I. (ed.), *Diagenetic Screening of Bone Samples; Tools to Aid Taphonomic and Archaeometric Investigations*. PhD dissertation, VU University, Amsterdam, Department for Geo- and Bioarchaeology, pp. 45–59 Available: http://dare.ubvu.vu.nl/handle/1871/40245

Hollund, H. I., Arts, N., Jans, M. M. E., and Kars, H., Are teeth better? Histological characterization of diagenesis in archaeological bone-tooth pairs and a discussion of the consequences for archaeometric sample selection and analyses. *International Journal of Osteoarchaeology*, **23**(6). doi: 10.1002/oa.2376.

Huisman, D. J. (ed.), 2009. *Degradation of Archaeological Remains*. Den Haag: Sdu Uitgevers.

Kars, H., and van Heeringen, R. M. (eds.), 2008. *Preserving Archaeological Remains In Situ: Proceedings of the 3rd Conference 7–9 December 2006, Amsterdam*. Geoarchaeological and

Bioarchaeological Studies 10. Amsterdam: Institute for Geo and Bioarchaeology, VU University.
Matthiesen, H., 2008. Detailed chemical analyses of groundwater as a tool for monitoring urban archaeological deposits: results from Bryggen in Bergen. *Journal of Archaeological Science*, **35**(5), 1378–1388.

Cross-references

Field Geochemistry
Organic Residues
Site Formation Processes
Soil Micromorphology

SOIL GEOMORPHOLOGY

Vance T. Holliday[1] and Rolfe D. Mandel[2]
[1]Anthropology and Departments Geosciences, University of Arizona, Tucson, AZ, USA
[2]Department of Anthropology, University of Kansas, Lawrence, KS, USA

Introduction

Few aspects of the environment are as intimately linked to the landscape as are soils, and this linkage emphasizes the important role of soils in geoarchaeology. At its most fundamental level, soil geomorphology is the study of genetic relationships between soils and landscapes (e.g., Ruhe, 1956; Ruhe, 1965; Schaetzl and Anderson, 2005). Its focus is on pedogenic and geomorphic processes and sometimes a strong component of hydrology in order to understand the distribution of soils in the present (contemporary soil geography) and in the past. In a much broader sense, however, soil geomorphology includes the investigation of soils as a means of studying and reconstructing the past, with a focus on soils as (1) clues to past environments (especially vegetation and climate) and past landscapes (Gerrard, 1992; Birkeland, 1999; Schaetzl and Anderson, 2005), (2) age indicators, and (3) stratigraphic markers (see the entry on "Soil Stratigraphy" in this volume). The focus here is on the relation between soils and landscapes and soils and time.

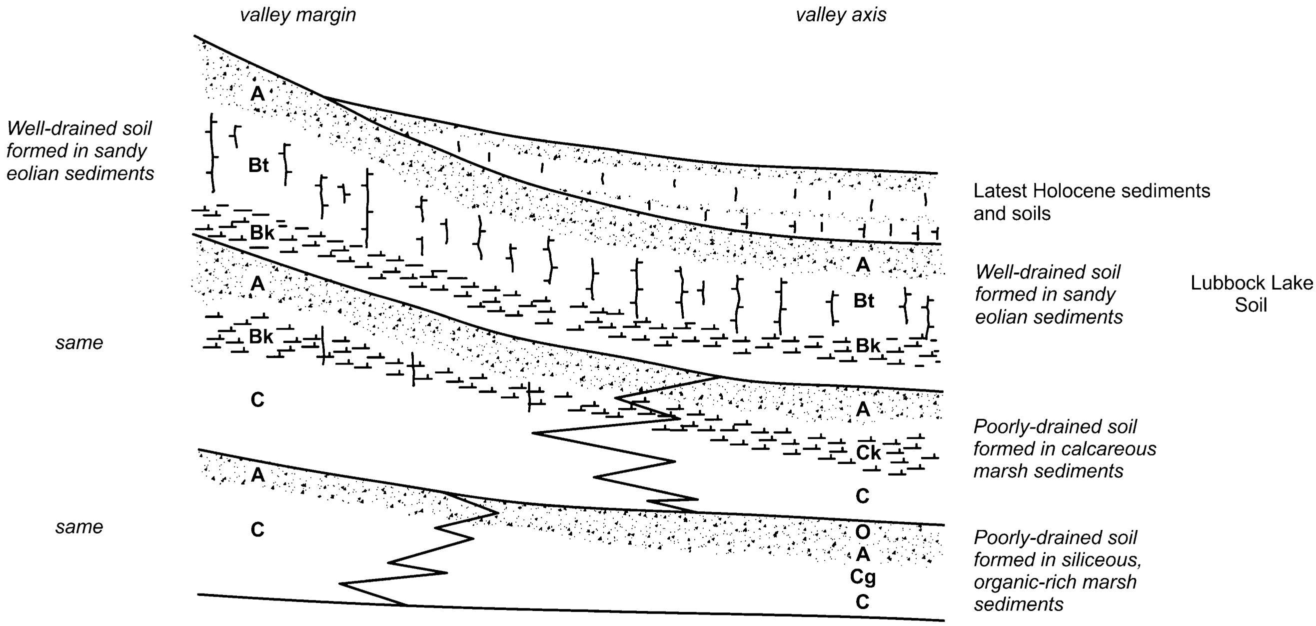
Soils and landscapes

Soils and archaeological sites are intimately related to the landscape. Investigating soils across past and present landscapes provides a means of reconstructing and understanding the regional environmental and geomorphic context of archaeological site settings and specific site locations, as well as regional site formation processes and aspects of the resources available to people in a region. Archaeological sites tend to occupy small segments of the landscape, but human activity may affect a much larger area, and in any case, people wander widely, well beyond the confines of sites, and in the process interact with the environment, including the landscape.

Soils are also important in reconstructing the evolution of landscapes and, consequently, the evolution of archaeological sites. Landscape evolution is an important external component of site formation processes. Landscapes form the physical framework or underpinning for people and their activities, and therefore for their resulting sites. As landscapes evolve, so do human activities, and so do sites. Soils are a key to recognizing and interpreting the evolutionary processes that shape the landscape and associated archaeological sites. The concept of landscape evolution is also (1) linked to soil stratigraphy because it places such stratigraphic sequences in three or even four dimensions; (2) an environmental indicator because landscape evolution can be linked to environmental change and because the evolution of the landscape itself, regardless of changes in other factors, represents a change in the environment from a human perspective; and (3) a means by which site locations can be predicted.

The variability of soils across a landscape due to topographic and hydrologic variability makes soils uniquely suited as indicators of past landscapes. Understanding the processes that produce soil variability and result in catenas (see the entry on "Soils" in this volume) provides an approach to making interpretations regarding past landscapes. This variability is related to the slope position and drainage characteristics of the soil. Ultimately, these factors are related to water movement over and through the soil. The rate and amount of water moving across the upper and middle segments of a slope are important in determining the presence or absence, and the amount and type, of erosion (in addition to determining vegetation characteristics), and the amount of water that moves into the soil is important in understanding weathering and solute transport. On lower slopes or at the foot of slopes, these factors, combined with groundwater characteristics, strongly influence sediment accumulation and solute input, in addition to vegetation and drainage, and they can contribute to soil *cumulization* (see entry on "Soil Stratigraphy" in this volume). The relative importance of surface movement of sediment and subsurface movement of solutes is dependent on slope angle and distance from slope crest, in addition to climate. A catena, therefore, results from the complex interplay between soil and slope processes and will be driven by the varying rates of erosion vs deposition on different parts of the slope. All landscapes with relief include zones of removal, transference, and accumulation.

Both stable and unstable catenas are present in middle and late Holocene strata at the Lubbock Lake site, Texas (Holliday, 1985a; Holliday, 1985b; Holliday, 1985c). The Lubbock Lake soil, formed in middle Holocene eolian sediments, illustrates a stable catena (Figure 1) where soil variability is due to varying topographic and hydrologic factors (and some parent material variation). The soil exhibits a valley-axis facies with a thicker, darker, locally cumulic surface horizon due to the more moist setting resulting from proximity to local marshes and high organic matter production, as well as local, slow



Soil Geomorphology, Figure 1 Generalized catenary relationships of soil-stratigraphic units at the Lubbock Lake site, Texas (Modified from Holliday, 2004: Figure 9.3).

aggradation. The valley-margin facies, in contrast, has a weakly expressed A horizon over a Bw-Bkw horizonation up to 2 m thick. The thickness of the soil is the result of rapid throughflow of water due to the coarse texture of the parent material, but the lack of illuvial clay and weaker expression of the A horizon is because less water moved into the soil due to rapid runoff and some erosion. The Lubbock Lake soil was buried along its middle and lower slopes during the late Holocene by slopewash and eolian deposits. Episodic sedimentation resulted in the formation of multistory, weakly expressed buried soils (Figure 1). This scenario is an example of an unstable catena.

A soil-geomorphic approach to an ancient paleocatena was used to reconstruct the paleo-landscape of hominins in Olduvai Gorge, Tanzania. Ashley and Driese (2000) identified a buried paleocatena in proximity to wetlands and dated it to ~1.75 Ma. The buried soils were then used to reconstruct the evolution of the local paleohydrology. The paleocatena was identified within a "cumulative red paleosol" formed in volcaniclastic parent material, and it was differentiated into an upslope and a downslope facies (over a distance of about 1 km). Compared to the downslope facies, the upslope facies was characterized by less evidence for plant rooting, greater clay translocation, and greater zeolitization (i.e., greater weathering of the volcaniclastic parent material). The downslope soil exhibited strong redoximorphic mottling, which was attributed to its proximity to an ancient lake. Also, the downslope soil exhibited evidence for two generations of redoximorphic features, separated by a phase of clay translocation, indicative of a shift from poorer drainage to better drainage and back to poor drainage. The changing drainage characteristics were attributed to fluctuations in lake level, among other factors (Ashley and Driese, 2000). By contrast, the upslope soil was oxidized and lacked redoximorphic features. Hence, the upslope setting was probably a drier and better drained site than the downslope one.

A reconstruction of soil-geomorphic relations was used in northwest Yucatán to answer questions about the degree of agricultural productivity necessary to support apparently high populations of ancient Maya in an agriculturally limited environment (Beach, 1998). The region is a -low-gradient plain. Soil variation results mostly from relatively minor topographic differences that divide the landscape into a coastal zone, a swamp estuary zone, a savanna zone, and a karst plain. The regional soil diversity is described largely on the basis of microrelief, which determines local drainage conditions.

In the coastal zone, the topography consists of beach ridges and swales. The soils are weakly expressed due to the youthfulness of the landscape (<5000 year BP), which apparently is "rejuvenated" by severe storms that cause erosion and uprooting of vegetation. Inland from the coastal zone is an extensive wetland estuary with mangrove swamp. Inland of the swamp estuary is a gradually rising zone of weathered limestone divided into a topographically lower and upper savanna characterized by swales and hillocks. In the lower savanna, groundwater seepage causes widespread precipitation of calcium carbonate and the formation of a dense calcrete. Thin but redder and more clayey soils are common throughout the upper savanna, in both depressions and hillocks. Soil development is significantly stronger in the upper savanna, probably because the landscape is better drained and drier, and because active precipitation of calcium carbonate, which maintains a relatively youthful landscape, is much less common. On the upland karst plain, soils are generally similar to those of the upper savanna in being relatively well developed. Soil variability is due to parent material lithology and to topographic setting. The soil studies in this region illustrate the severe limitations on agriculture (Beach, 1998, 786–787). About 50 % of the landscape has no soil. Only about 20 % of the soils are deep and fertile. Erosion probably was not and is not a factor in the soil patterns owing to the very low relief. If intensive agriculture had been practiced, it might have been within walled mounds and fields, where water and fertilizer were easily accessible.

Soils and time

The influence of time on soil formation is a unique characteristic of pedogenesis among geomorphic processes that, like topographic variability, serves to distinguish soils and soil-forming processes from other geomorphic phenomena. The passage of time allows pedogenic processes operative at a given location to alter the parent material and produce a soil. The physical, chemical, and biological processes of soil formation generally are much slower than many if not most processes of sedimentation and erosion. Moreover, most soil-forming processes are so slow that their effect on the soil is markedly time dependent (Birkeland, 1999, 144).

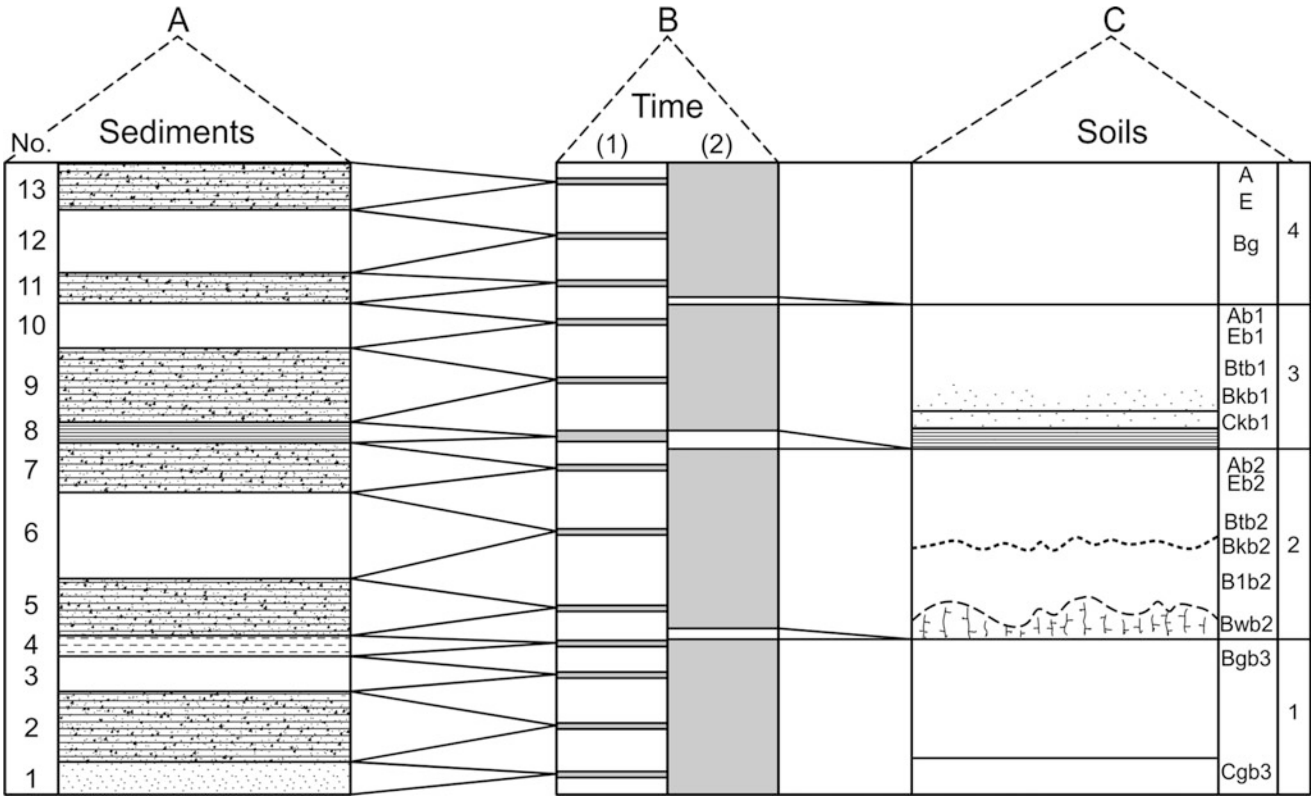
Time as a factor of soil formation is a key concept in soil geomorphology and has driven much soil-geomorphic research (Yaalon, 1975; Yaalon, 1983; Knuepfer and McFadden, 1990; Birkeland, 1999). Because time is an important consideration of much archaeological research, the time-factor concept of soil genesis can also play a significant role in geoarchaeological research (Holliday, 1990; Holliday, 1992; Holliday, 2004). The concept that some time must elapse before a soil can form is a significant aspect of soil development in an archaeological context.

The association of archaeological materials with a soil or the presence of a soil or soils in a stratigraphic sequence at an archaeological site is of direct and fundamental significance to the interpretation of the archaeological record. Soils require some amount of time to form, and the development of a soil requires a relatively stable landscape, one that is neither aggrading nor eroding at rates that exceed pedogenesis. Thus, a soil denotes the passage of time under conditions of relative landscape stability. A buried soil in a stratigraphic sequence, therefore, denotes a hiatus in deposition, i.e., a kind of unconformity. In such a sequence, the sediment (which is the parent material for the soil) may have accumulated rapidly or slowly, but a significant period of no deposition and no erosion had to occur in order for the soil to form. Under some circumstances, deposition can occur quickly – possibly in a matter of days, years, or decades. Soil formation, in contrast, almost always takes longer: usually at least a century or several centuries and commonly millennia (Figure 2), though see exceptions below (e.g., Birkeland, 1999; Holliday, 2004). In a stratigraphic sequence, the accumulation of deposits represents the passage of time sedimentologically, and the alteration or weathering of those deposits represents the passage of time pedologically. In settings where sedimentation is episodic and buried soils are common, soil formation may take up a significant amount of the time represented in a stratigraphic sequence (Figure 2) (e.g., Kraus and Bown, 1986; Holliday, 1992).

> In archaeological investigations, consideration of landscape stability, as indicated by soil development, is important in locating cultural deposits, interpreting artifact associations and contexts, defining site stratigraphy, reconstructing the depositional and landscape history, and establishing cultural chronologies. (Mandel and Bettis, 2001a, 175)

These fundamental characteristics of soil formation and time are of paramount significance in geoarchaeological research. In searching for archaeological sites or other evidence of human activity in stratigraphic sequences with buried soils, the surfaces of the soils (i.e., the A horizons) will be more likely than other parts of the soil or parent material to contain artifacts and features because (1) they represent surfaces that were stable for some duration of time, and (2) human occupation is more likely on a stable surface than it is on a landscape undergoing rapid sedimentation. This aspect of A horizons has influenced the development of strategies in surveying and prospecting for archaeological sites, especially in buried settings (Michlovic et al., 1988; Ferring, 1992; Picha and Gregg, 1993; Stafford, 1995).

Furthermore, the degree of soil development can be of considerable help in deciphering the archaeological record associated with buried soils and buried surfaces. Put simply, buried soils can be viewed as representing time in two basic stratigraphic forms: (1) as weakly developed soils, each representing a relatively short time (i.e., a relatively brief interval of soil formation between periods of deposition or between periods of deposition and erosion), or (2) as better developed soils representing longer intervals of nondeposition and landscape stability (though soil development is expressed in a wide continuum of degrees of development). The relative amount of time taken up by pedogenesis in these settings will still greatly exceed that taken up by deposition (Holliday, 2004, 140–144), but the time will be parceled out among the individual deposits and soils (Figure 2). Archaeological sites in these settings will be well stratified with superposition of artifacts and features that resulted from serial occupation of sites (Ferring, 1986).



Soil Geomorphology, Figure 2 Illustration of a hypothetical alluvial sequence consisting of layers 1 through 13 (column A) and associated soils 1 through 4 (column C) (Modified from Kraus and Bown, 1986: Figure 1). Column B indicates the relative proportion of time occupied by deposition (B1) and soil formation (B2) (Modified from Holliday, 2004: Figure 7.1).

In contrast to weakly developed soils, more strongly expressed soils represent long intervals of soil formation between periods of instability. Archaeologically, this is particularly significant because slow deposition during multiple episodes of occupation results in accumulation of archaeological debris as mixed assemblages on paleosurfaces (Ferring, 1986). That is, the archaeological evidence for repeated occupations is compressed into the A horizon of a single surface, thereby forming archaeological palimpsests. Assuming "that the probability of cultural utilization of a particular landscape position is equal for each year, it follows that the surfaces which remain exposed for the longest time (i.e., the surfaces of the better developed soils) would represent those with the highest probability of containing cultural remains" (Hoyer, 1980, 61). The formation of a soil at an archaeological site, therefore, can profoundly influence the nature of the archaeological record and interpretations of the cultural history of the locality. Long spans of time are represented by the surface of a well-developed soil and, therefore, long records of habitation can be compressed into zones only a few centimeters thick. In searching for archaeological sites, the A horizons of well-expressed buried soils are more likely than weakly developed ones in the same area to contain occupation debris, but that debris is more likely to be a mixture of artifacts from multiple occupations.

There are several notable, archaeologically significant exceptions to the concept of brief, relatively rapid intervals of sedimentation or erosion separated by relatively lengthy intervals of stability and pedogenesis. Bogs or marshes (Histosols) are characterized by prolonged accumulation of organic matter, and they do not necessarily require surface stability to form. Other cumulizing or accretionary settings, locally found on many landscapes, also are exceptions. In some floodplain or toe slope settings, multiple, very weakly developed soils occur, formed during brief intervals (a few years) of stability between episodes of deposition. These soils are products of gradual accumulation of organic matter derived from in situ vegetation and detrital sources. A recent systematic study of late Quaternary landscape evolution in the US Central Plains documented widespread, deeply buried cumulic paleosols with weakly to moderately developed profiles that represent Paleoindian-age landscapes in terrace fills of high-order streams, in alluvial fans, and in draws in areas of the High Plains (Mandel, 2008). These paleosols have become targets in archaeological surveys that focus on the early record of human occupation in the Great Plains (Mandel, 2006).

With archaeological surveys, the problem of locating sites of a particular cultural period is one of determining where in the landscape sediments of that period are preserved (Artz, 1985; Mandel, 1992). In other words, knowledge of the distribution of the various-age deposits that comprise landscapes is essential in order to evaluate those landscapes for evidence of past human occupation (Bettis, 1992, 132; Mandel and Bettis, 2001a; Mandel, 2006; Beeton and Mandel, 2011). In most areas, soil variability across the landscape is an important indicator for estimating the age of landforms and sediment assemblages that underlie them. Many studies have demonstrated that the magnitude of soil development provides important clues to the relative ages of geomorphic surfaces and underlying deposits (e.g., Yaalon, 1971; Vreeken, 1975; Gile et al., 1981; Harden, 1982; McFadden and Weldon, 1987; Birkeland and Burke, 1988; Karlstrom, 1988; Dethier, 1988; Bettis, 1992; Holliday, 1992; Birkeland, 1999). Because surface soils can provide relative time control and can be mapped (see the entry on "Soil Survey" in this volume), they may be used to devise "quick and dirty" strategies for assessing the cultural resource potential of a survey area.

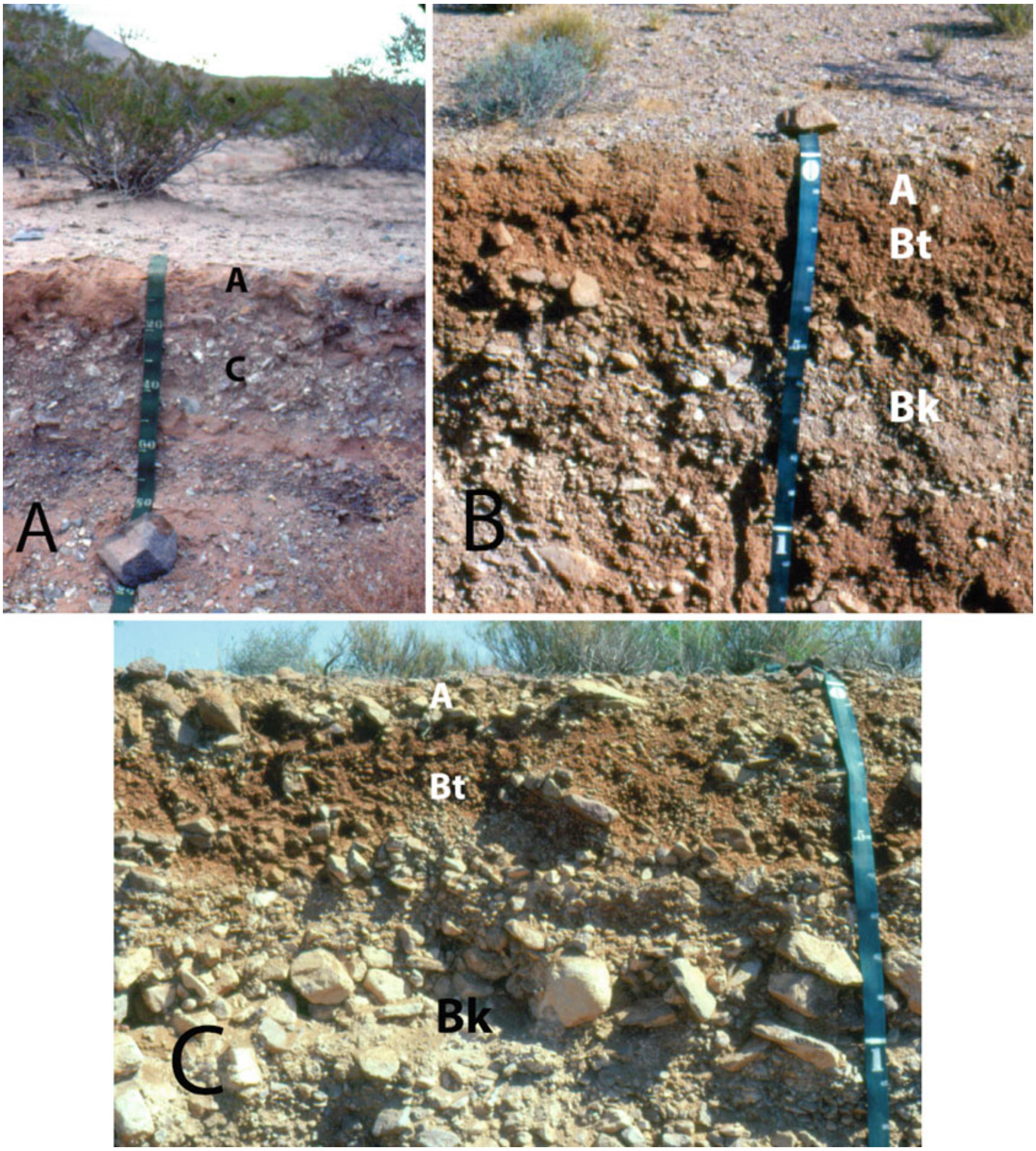
Soil "chronosequences" are especially useful in finding or interpreting archaeological sites at the surface. A soil chronosequence is a group of soils whose properties vary primarily as a function of age variability (Figure 3). The soils in a chronosequence formed in similar parent materials in similar landscape positions under a similar climate and vegetation. The primary difference in the genesis of the soils is that their age is different from landscape to landscape. For example, many chronosequences are defined for the surfaces of a set of alluvial terraces whose ages vary but where the parent materials and landscape settings are the same and the climate and biota have changed little (or the changes can be controlled for). In such a terrace chronosequence, the soils on the higher terraces typically will have more strongly developed profiles than the soils on the lower terraces because the higher terraces are older, and there was more time for pedogenesis (Figure 4) (e.g., Holliday, 2004: Table 7.2). As a corollary to this definition of a chronosequence, in an area where there are a number of soils and where the influence of parent material, landscape position, climate, flora, and fauna was similar among the soils and did not vary through time, the soils with stronger profile development probably are older than those that are less developed.

Soil chronosequences also occur across terraces where laterally inset alluvial fills aggraded to approximately the same elevation. For example, in the South Fork Big Nemaha River valley of southeastern Nebraska, Mandel and Bettis (2001b) observed a complex mosaic of soils across the T-1 terrace, with a well-developed Mollisol characterized by a thick A-Bt profile occurring near the valley wall, a less-developed Mollisol with a thin A-Bw profile occurring in the middle of the terrace, and a poorly developed Mollisol with an A-C profile near the modern channel of the river. A long cutbank that formed perpendicular to the axis of the valley revealed that at least three laterally inset fills occur beneath the T-1 terrace, and subsequent radiocarbon dating of the fills indicated significant time-transgression going from the proximal to the distal portions of the T-1 terrace (Figure 5). Hence, soil variability on the terrace represents the effect of time, with the most poorly developed soils occurring at the top of the youngest alluvial fill, proximal to the channel, and the most strongly developed soils occurring at the top of the oldest fill, distal to the channel.

Once a chronosequence is identified and investigated, it can be used as a dating tool in several ways. One application is simply for stratigraphic correlation of modern surfaces. Knowing that a soil of a given age in a particular landscape setting will exhibit a certain morphology is very useful for estimating the age of soils and, hence, landscapes throughout a region. Understanding the age of a landscape can then aid in predicting the age limits of archaeological finds on the surface and predicting the likelihood for sites below the surface. For example, in North America, the surface of an alluvial terrace with soil development suggestive of tens of thousands of years of stability and soil genesis could have the full age range of archaeological occupations known on the continent (i.e., the past ~15,000 years).

Bettis (1992) and Bettis and Hajic (1995) have developed a model to predict the ages of alluvial landscapes, alluvial deposits, and associated archaeological remains for Holocene streams in the Midwestern United States (Table 1). The model is intended to aid archaeologists in adequately sampling the archaeological record, predicting site locations, and estimating the ages of sites. The distinguishing criteria for differentiating Historic, late Holocene, and early and middle Holocene alluvial deposits are easily observed properties of deposits and soils that can be recorded by archaeologists with only modest knowledge of soils and geomorphology (Bettis, 1992, 120). The model is based on soil morphology and on color and mottling characteristics in the subsoil alluvium. The resulting model is a good example of increased soil development as well as mottling and subsoil iron oxidation with time.

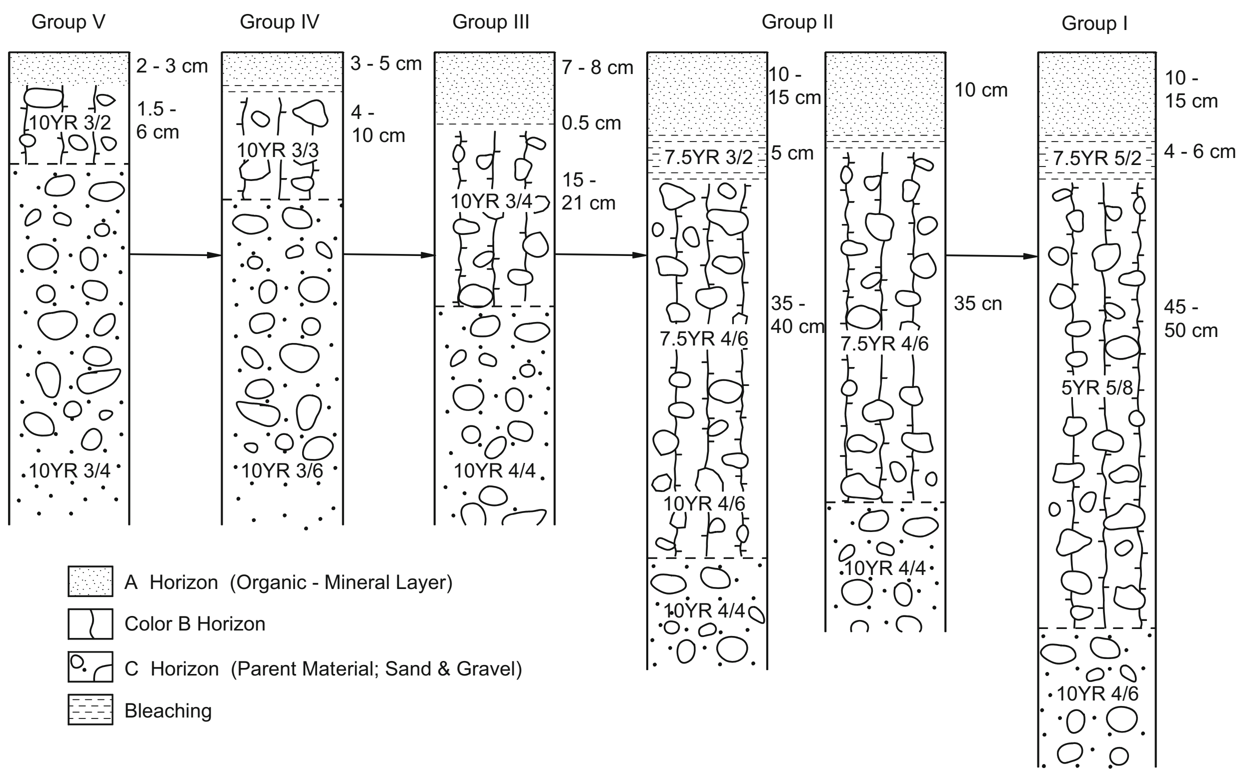
In a study of eight archaeological sites in the central Upper Peninsula of Michigan, Anderton (1999) used soils to provide temporal context for cultural deposits. The sites, which are associated with mid- and late Holocene paleoshorelines of the ancestral Great Lakes, contain stone flakes and fire-cracked rock but rarely yield temporally diagnostic artifacts or ^{14}C-datable materials. Based on the ages of the former shoreline, most researchers had assumed that the sites represented Archaic occupations dating to ca. 5000–2000 BP. However, Anderton (1999) suspected that former shorelines were also occupied by later Woodland cultures. By considering the expected pedological and archaeological characteristics, he developed



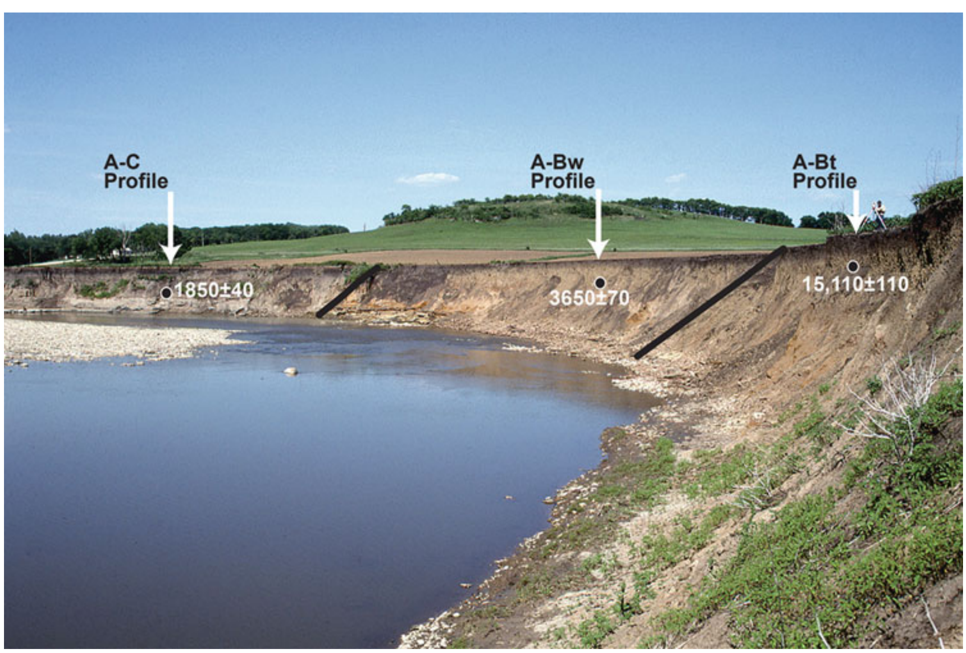
Soil Geomorphology, Figure 3 A soil chronosequence illustrating the development of the Bk horizon (zones of secondary carbonate accumulation) in piedmont alluvium along the Rio Grande River near Las Cruces, New Mexico (following Gile et al., 1981): (**a**) Alluvium <1000 years old with minimal carbonate accumulation or horizonation; (**b**) alluvium ~6000 years old with weak but distinct carbonate accumulation; (**c**) alluvium >25,000 year old with well-expressed Bk horizon. The Bt horizon is better expressed with time, but its characteristics (reddening and increased content of illuvial clay) are not well illustrated in photos. Scales are in centimeters (Photos by Vance Holliday).

a soil-artifact context model that provided a preliminary means of relative dating. Specifically, sites that were correlative with shoreline development (i.e., Archaic occupations) have artifacts that are deep within the soil profile; they reveal soil horizon boundaries that cut across middens, and some recovered artifacts are iron stained from spodic horizon development. By contrast, sites that post-date shoreline development (i.e., Woodland occupations) have artifacts that are at or very near ground surface. Also, Woodland cultural features, if present, cut across soil horizons, and the artifacts generally are not iron stained.

In the Old World, the chronosequence approach has been successfully applied in geoarchaeological contexts in Greece. Research on late Quaternary stratigraphy, geomorphology, and geoarchaeology resulted in the definition of soil "maturation stages" (MS 1–6, ordered youngest to oldest) based on the degree of color (rubification) and structural expression and clay film and



Soil Geomorphology, Figure 4 An example of soil development through time as illustrated by soil formation in a terrace chronosequence in Scotland (Robertson-Rintoul, 1986: Figure 5) (Modified from Holliday (2004: Figure 7.17)). The alpha-numeric notations with "YR" are Munsell soil colors and indicate progressive reddening due to iron oxidation.



Soil Geomorphology, Figure 5 The north bank of the South Fork Big Nemaha River in southeastern Nebraska showing a series of laterally inset alluvial fills beneath the T-1 terrace. The magnitude of soil development varies across the terrace and is an example of a chronosequence directly related to the age of the fills. All of the radiocarbon ages were determined on charcoal (Photo by Rolfe Mandel).

Soil Geomorphology, Table 1 Criteria used to group Upper Midwestern alluvial deposits into age-morphologic groups[a]

Age-morphologic group	Bedding	Weathering zone[b]	Mottles	Surface soil (horizon sequence; B horizon color)
EMH[c]	Restricted to the lower part of the section	O, MO, R, or U in part of some sections	Common; brown, reddish- brown, and/or gray	A-E-Bt or A-Bt; brown B horizon
LH[d]	Usually restricted to the lower part of the section	Color usually 10YR hue,[e] values 4 or less, chroma 3 or less; disseminated organic carbon imparts dark colors; may be O or U, but the matrix colors are dark because of organic carbon content	Rare; usually not present	A-Bw; dark-colored B horizon
Historic	Present throughout section if >50 cm in thickness	O; MO; R; some sections dark colored because of high organic carbon content	Can be present or absent; brown, reddish brown, or gray	A-C; no B horizon

[a]From Bettis (1992: Table 4–3)
[b]*O* oxidized, *M* mottled, *R* reduced, *U* unoxidized
[c]*EMH* early and middle Holocene
[d]*LH* late Holocene
[e]Munsell color designation

Soil Geomorphology, Table 2 General soil-stratigraphic and soil-geomorphic characteristics of alluvium on the Argolid and Argive Plain of southern Greece[a]

Soil name	Horizon sequence	Diagnostic features	MS[b]	Age of alluvium
Kranidhi	A-C	Thin to nonexistent A horizon; stratified parent material	1	
Upper member Flambouro	A-C	Thin A horizon; some mixing of parent material stratification	1	
Lower member Flambouro	A-Bw/Bk-C	Well-developed A horizon; weak Bk 10YR 4/3 B horizon	1	
Pikrodafni	A-Bt/Btk-C	Well-developed A horizon; weak-moderate Bk 5YR 4/4 Bt horizon w/few, thin clay films	2	2700–1400 BC
Upper Mbr Loutro	A-Btk-C	Eroded A horizon; moderate Bk 7.5YR 4/4 Bt horizon w/common, thin clay films	3/4	45,000–32,000 year
Middle Mbr Loutro	A-Btk-C	Eroded A horizon; moderate-strong Bk thick 5YR 4/6 Bt horizon w/thin, common clay films; no stratification in upper 2 m	5	>60,000 year
Lower Mbr Loutro	A-Btk-C	Eroded A horizon; strong Bk thick 2.5YR 3/6 Bt horizon; no stratification in upper 3 m	6	>250,000 year
Upland soil	A-Bt-C	Thick, dark A horizon; thick Bt horizon w/thick, continuous clay films		

[a]Data from Pope and van Andel (1984: Tables 1 and 2) and van Andel (1998: Figs. 6) (Modified from Holliday, 2004: Table 6.1)
[b]Maturation stage

calcic horizon development (Table 2) (Pope and van Andel, 1984; van Andel, 1998). The sequence is calibrated on the basis of numerical dating methods. One geoarchaeological example of the use of the MS index is in assessing the association of mid-Paleolithic artifacts with buried soils throughout Greece. Many artifacts are found in areas that were once internally drained basins with ponds, associated with sediments expressing little or no pedogenesis, implying brief occupation of an active landscape (van Andel, 1998, 383). Other artifacts are found within "very mature Bt horizons," suggesting occupation of a slowly aggrading but otherwise stable landscape lacking in the attractions offered by the wetlands (van Andel, 1998, 383).

Bibliography

Anderton, J. B., 1999. The soil-artifact context model: a geoarchaeological approach to paleoshoreline site dating in the Upper Peninsula of Michigan USA. *Geoarchaeology*, **14**(3), 265–288.

Artz, J. A., 1985. A soil-geomorphic approach to locating buried Late-Archaic sites in northeast Oklahoma. *American Archaeology*, **5**(2), 142–150.

Ashley, G. M., and Driese, S. G., 2000. Paleopedology and paleohydrology of a volcaniclastic paleosol interval: implications for early Pleistocene stratigraphy and paleoclimate record, Olduvai Gorge, Tanzania. *Journal of Sedimentary Research*, **70**(5), 1065–1080.

Beach, T., 1998. Soil constraints on northwest Yucatán, Mexico: pedoarchaeology and Maya subsistence at Chunchucmil. *Geoarchaeology*, **13**(8), 759–791.

Beeton, J. M., and Mandel, R. D., 2011. Soils and Late-Quaternary landscape evolution in the Cottonwood River basin, east-central Kansas: implications for archaeological research. *Geoarchaeology*, **26**(5), 693–723.

Bettis, E. A., III, 1992. Soil morphologic properties and weathering zone characteristics as age indicators in Holocene alluvium in the Upper Midwest. In Holliday, V. T. (ed.), *Soils in Archaeology: Landscape Evolution and Human Occupation*. Washington, DC: Smithsonian Institution Press, pp. 119–144.

Bettis, E. A., III, and Hajic, E. R., 1995. Landscape development and the location of evidence of Archaic cultures in the Upper Midwest. In Bettis, E. A., III (ed.), *Archaeological Geology of the Archaic Period in North America*. Boulder, CO: Geological Society of America. GSA Special Paper 297, pp. 87–114.

Birkeland, P. W., 1999. *Soils and Geomorphology*, 3rd edn. New York: Oxford University Press.

Birkeland, P. W., and Burke, R. M., 1988. Soil catena chronosequences on eastern Sierra Nevada moraines, California, U.S.A. *Arctic and Alpine Research*, **20**(4), 473–484.

Dethier, D. P., 1988. *The Soil Chronosequence along the Cowlitz River, Washington*. Washington, DC: Government Printing Office. US Geological Survey Bulletin 1590-F.

Ferring, C. R., 1986. Rate of fluvial sedimentation: implications for archaeological variability. *Geoarchaeology*, **1**(3), 259–274.

Ferring, C. R., 1992. Alluvial pedology and geoarchaeological research. In Holliday, V. T. (ed.), *Soils in Archaeology: Landscape Evolution and Human Occupation*. Washington, DC: Smithsonian Institution Press, pp. 1–39.

Gerrard, J., 1992. *Soil Geomorphology: An Integration of Pedology and Geomorphology*. London: Chapman and Hall.

Gile, L. H., Hawley, J. W., and Grossman, R. B., 1981. *Soils and Geomorphology in the Basin and Range Area of Southern New Mexico: Guidebook to the Desert Project*. Socorro, NM: New Mexico Bureau of Mines and Mineral Resources. Memoir 39.

Harden, J. W., 1982. A quantitative index of soil development from field descriptions: examples from a chronosequence in central California. *Geoderma*, **28**(1), 1–28.

Holliday, V. T., 1985a. Morphology of late Holocene soils at the Lubbock Lake archeological site, Texas. *Soil Science Society of America Journal*, **49**(4), 938–946.

Holliday, V. T., 1985b. Early Holocene soils at the Lubbock Lake archeological site, Texas. *Catena*, **12**(1), 61–78.

Holliday, V. T., 1985c. Archaeological geology of the Lubbock Lake site, Southern High Plains of Texas. *Geological Society of America Bulletin*, **96**(12), 1483–1492.

Holliday, V. T., 1990. Pedology in archaeology. In Lasca, N. P., and Donahue, J. (eds.), *Archaeological Geology of North America*. Boulder, CO: Geological Society of America. GSA Centennial, Vol. 4, pp. 525–540.

Holliday, V. T., 1992. Soil formation, time, and archaeology. In Holliday, V. T. (ed.), *Soils in Archaeology: Landscape Evolution and Human Occupation*. Washington, DC: Smithsonian Institution Press, pp. 101–117.

Holliday, V. T., 2004. *Soils in Archaeological Research*. New York: Oxford University Press.

Hoyer, B. E., 1980. The geology of the Cherokee Sewer Site. In Anderson, D. C., and Semken, H. A., Jr. (eds.), *The Cherokee Excavations: Holocene Ecology and Human Adaptations in Northwestern Iowa*. New York: Academic, pp. 21–66.

Karlstrom, E. T., 1988. Rates of soil formation on Black Mesa, northeast Arizona: a chronosequence in late Quaternary alluvium. *Physical Geography*, **9**(4), 301–327.

Knuepfer, P. L. K., and McFadden, L. D. (eds.), 1990. *Soils and Landscape Evolution: Proceedings of the 21st Binghamton Symposium*. Amsterdam: Elsevier.

Kraus, M. J., and Bown, T. M., 1986. Paleosols and time resolution in alluvial stratigraphy. In Wright, V. P. (ed.), *Paleosols: Their Recognition and Interpretation*. Princeton: Princeton University Press, pp. 180–207.

Mandel, R. D., 1992. Soils and Holocene landscape evolution in central and southwestern Kansas: implications for archaeological research. In Holliday, V. T. (ed.), *Soils in Archaeology: Landscape Evolution and Human Occupation*. Washington, DC: Smithsonian Institution Press, pp. 41–117.

Mandel, R. D., 2006. The effects of late quaternary landscape evolution on the archaeology of Kansas. In Hoard, R. J., and Banks, W. E. (eds.), *Kansas Archaeology*. Lawrence, KS: University Press of Kansas, pp. 46–75.

Mandel, R. D., 2008. Buried Paleoindian-age landscapes in stream valleys of the Central Plains, USA. *Geomorphology*, **101**(1–2), 342–361.

Mandel, R. D., and Bettis, E. A., III, 2001a. Use and analysis of soils by archaeologists and geoscientists: a North American perspective. In Goldberg, P., Holliday, V. T., and Ferring, C. R. (eds.), *Earth Sciences and Archaeology*. New York: Kluwer Academic/Plenum Publishers, pp. 173–204.

Mandel, R. D., and Bettis, E. A., III, 2001b. *Late Quaternary Landscape Evolution in the South Fork of the Big Nemaha River Valley, Southeastern Nebraska and Northeastern Kansas*. Lincoln, NE: Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska at Lincoln. Guidebook No. 11.

McFadden, L. D., and Weldon, R. J., II, 1987. Rates and processes of soil development on Quaternary terraces in Cajon Pass, California. *Geological Society of America Bulletin*, **98**(3), 280–293.

Michlovic, M. G., Hopkins, D. G., and Richardson, J. L., 1988. An interdisciplinary procedure for the identification and study of archaeological sites in sedimentary contexts. *Soil Survey Horizons*, **29**(1), 3–8.

Picha, P. R., and Gregg, M. L., 1993. Chronostratigraphy of Upper James River floodplain sediments: implications for southeastern North Dakota archaeology. *Geoarchaeology*, **8**(3), 203–215.

Pope, K. O., and van Andel, T. H., 1984. Late Quaternary alluviation and soil formation in the southern Argolid: its history, causes and archaeological implications. *Journal of Archaeological Science*, **11**(4), 281–306.

Robertson-Rintoul, M. S. E., 1986. A quantitative soil-stratigraphic approach to the correlation and dating of post-glacial river terraces in Glen Feshie, western Cairngorms. *Earth Surface Processes and Landforms*, **11**(6), 605–617.

Ruhe, R. V., 1956. Geomorphic surfaces and the nature of soils. *Soil Science*, **82**(6), 441–456.

Ruhe, R. V., 1965. Quaternary paleopedology. In Wright, H. E., and Frey, D. G. (eds.), *The Quaternary of the United States*. Princeton: Princeton University Press.

Schaetzl, R. J., and Anderson, S., 2005. *Soils: Genesis and Geomorphology*. New York: Cambridge University Press.
Stafford, C. R., 1995. Geoarchaeological perspectives on paleolandscapes and regional subsurface archaeology. *Journal of Archaeological Method and Theory*, **2**(1), 69–104.
Van Andel, T. H., 1998. Paleosols, red sediments, and the Old Stone Age in Greece. *Geoarchaeology*, **13**(4), 361–390.
Vreeken, W. J., 1975. Principal kinds of chronosequences and their significance in soil history. *Journal of Soil Science*, **26**(4), 378–394.
Yaalon, D. H., 1971. Soil-forming processes in time and space. In Yaalon, D. H. (ed.), *Paleopedology: Origin, Nature and Dating of Paleosols*. Jerusalem: International Society of Soil Science and Israel Universities Press, pp. 29–39.
Yaalon, D. H., 1975. Conceptual models in pedogenesis: can soil-forming functions be solved? *Geoderma*, **14**(3), 189–205.
Yaalon, D. H., 1983. Climate, time and soil development. In Wilding, L. P., Smeck, N. E., and Hall, G. F. (eds.), *Pedogenesis and Soil Taxonomy: Part 1, Concepts and Interactions*. Amsterdam: Elsevier. Developments in Soil Science 11A, pp. 233–251.

Cross-references

Geomorphology
Landscape Archaeology
Site Formation Processes
Soil Stratigraphy
Soil Survey
Soils
Stratigraphy

SOIL MICROMORPHOLOGY

Panagiotis Karkanas[1] and Paul Goldberg[2]
[1]Ephoreia of Palaeoanthropology & Speleology of Southern Greece, Athens, Greece
[2]Department of Archaeology, Emeritus at Boston University, Boston, MA, USA

Definitions

Birefringence fabric (b-fabric): patterns of orientation and distribution of interference colors in the micromass seen in crossed-polarized light.

Fabric (micro): the spatial arrangement of the soil constituents, including solid material, pores, and their shape, size and frequency.

Groundmass: the coarse and fine material that forms the basic material of the soil in thin section.

Microfacies: the body of sediment seen in thin section with microscopic characteristics such as composition, grain size, and sedimentary structures that are recognizably different from surrounding sediments.

Pedofeature: discrete fabric units in soil material. They are characterized by different concentrations in one or more components or internal fabric from the adjacent groundmass.

Petrographic or polarized light microscope: a microscope equipped for observation of thin sections in transmitted polarized light.

Sedimentary structures: bedding and surface features produced at the time of deposition.

Structure (micro): size, shape, and arrangement of particles, voids, and aggregates of the soil.

Soil micromorphology: the study of undisturbed soil and related materials at the microscopic level.

Thin section: a thin slice (ca. 30 µm thick) of intact material glued onto a glass slide.

Introduction

Soil micromorphology is the microscopic study of the soil, and since it usually employs the use of petrographic thin sections, it is similar to the geological discipline of petrography. The basic analytical equipment of soil micromorphology is the petrographic or polarized light microscope. Invented in the nineteenth century, the petrographic microscope was initially used to identify rock-forming minerals, and its application to sediments (sedimentary petrography) was undertaken by the English geologist Henry Clifton Sorby in the 1860s. Nowadays, petrographic microscopy is applied to numerous disciplines, including pedology, biology, archaeology, and environmental as well as material sciences. The application of petrographic microscopy to geoarchaeological contexts is relatively recent, but it is a corollary of the development of soil micromorphology and the interest of pedologists and geologists in archaeology.

History of application

In pedology, the use of the petrographic microscope began with Kubiëna (1938), who was primarily interested in using the internal organization of a soil to interpret its genesis. Soils are generally fine grained and form by sub-macroscopic processes, such as vertical transportation of fine material, solution and colloidal movements, and chemical alterations. The soil groundmass is part of a dynamic system that responds to these processes and leads to the formation of microscopic fabrics and pedofeatures that are related to soil development and origin. Therefore, the microscopic study of soils is a physical continuation of macroscopic observations of their morphology. A considerable body of literature exists on the application of soil micromorphology in pedology, including studies of fossil soils (paleosols) that have provided significant data for the study of Quaternary environments (Macphail, 1986; Macphail et al., 1987; Goldberg and Macphail, 2006).

As early as the end of the nineteenth century, petrographic methods were used to understand the genesis of limestone, and later, in the early 1950s, the concept of microfacies was employed in the study of carbonate and similar sediments (Flügel, 2004). However, clastic sedimentology is first concerned with field observation of bedding and sedimentary structures. Most sedimentary

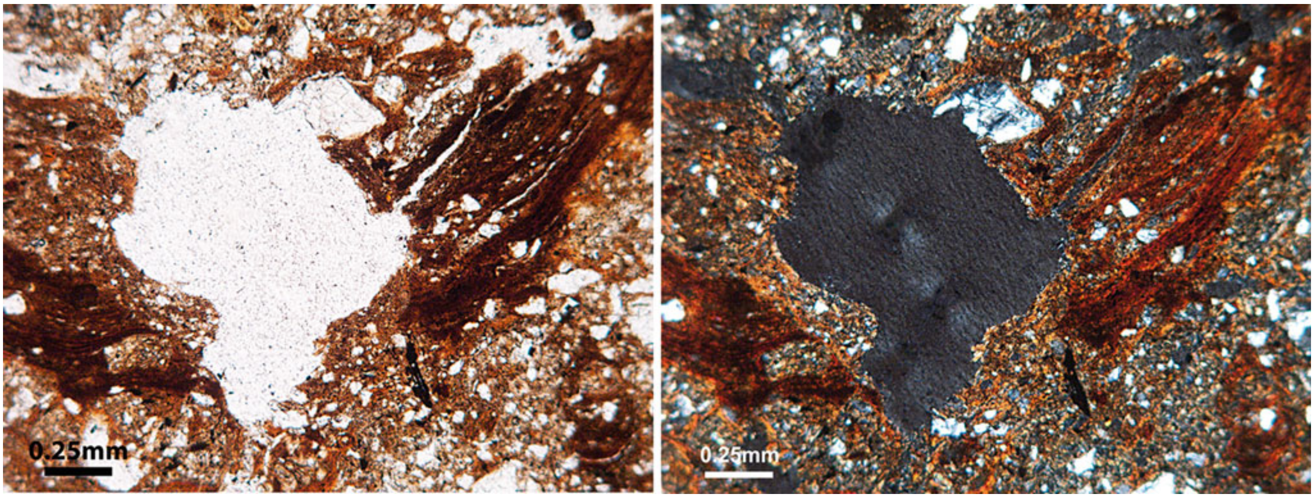
Soil Micromorphology, Figure 1 Micromorphological sampling. Carved out blocks of sediment (**a**) are jacketed with gypsum cloth (**b**) to ensure safe removal. Note that the lowermost sample (no. 157221) was encased in plaster of Paris to prevent collapse of the loose sand in its lower part. Caves PP5-6, Mossel Bay, South Africa.

environments are characterized by a variety of textures, and fine-grained sediment represents a fraction of the continuum. Therefore, very few petrographic studies of fine-grained sediment outside of carbonate sediments have been conducted. Such studies are mainly focused on marine muds (Förstner et al., 1968; Kuehl et al., 1988, 1991) or colluvial and mass wasting deposits (Mücher et al., 2010, and references therein).

Cornwall (1958) was the first to apply micromorphology in an archaeological context, but it was not until the 1980s that micromorphology really began to be applied in archaeology (Goldberg, 1980; Courty et al., 1989). The need for a contextual approach in archaeology has found its implementation in micromorphological analysis. Archaeological deposits, in most cases, are difficult to study and interpret through field observations alone. They have a complex macrostructure, are mostly fine grained, have diverse organic and minerogenic compositions, and commonly lack obvious macroscopic sedimentary structures. Thus, microscopic study is the most logical tool to provide the basis for characterizing archaeological deposits. Similarly, depositional processes can be studied to provide the initial and basic framework for applying other techniques that can further elucidate details of formation processes. Micromorphological applications in archaeology have increased markedly during the last three decades, resulting in increased recognition of anthropogenic sedimentary processes. A new dimension in the application of micromorphology in archaeology is the introduction of microfacies as used in sedimentology (Courty, 2001). Realization has gradually emerged that, in order to provide a better integration of microscopic techniques into the archaeological record, concepts and methods of sedimentology have to be adopted. Sediments dominate archaeological settings, and therefore microfacies analysis provides a new tool for refining visual classification of features. Classification of facies across strata is based on morphological and lithological similarities that are assumed to have similar origins and relate to the same mode of deposition (Courty, 2001). More and more studies on site formation processes are using the concept of microfacies with successful results (Macphail et al., 2004; Goldberg et al., 2009; Kourampas et al., 2009; Díaz and Eraso, 2010; Karkanas et al., 2011).

Methodology and techniques

The major methodological difference between a petrographic thin section and micromorphological thin section is in the preparation of the samples: petrography normally employs rocks and indurated materials, whereas micromorphological samples are typically nonconsolidated. The first step in micromorphology is to take an undisturbed, oriented sample from excavated or natural profiles, or even cores (Figure 1). Several techniques are employed, each having its limitations (Goldberg and Macphail, 2003). One of the most typical sampling techniques is the use of Kubiena boxes, metal boxes with double lids. During sampling, one lid is removed, and the frame of the box is inserted into the soil. Then, the frame is dug out, and the lid is replaced. Kubiena boxes are suitable for relatively firm and stone-free soils or sediments. However, archaeological deposits are very heterogeneous and not always consolidated. There is substantial lateral and vertical variation, and sediments can change from very coarse to fine grained over only a few mm; they can also commonly contain coarse clasts of rock, pottery, lithics, or bones, which interfere with sampling. Complex layering and lamination as well as inclined contacts are often observed in archaeological profiles. In order to understand how these changes were formed, they must be included in a single sample that preserves all features intact. It is thus not practical to use Kubiena boxes, and a large monolith is obviously required (Figure 1).



Soil Micromorphology, Figure 2 Photomicrograph of compound layered dusty clay and silt infilling and juxtaposed silt coating; *left*: plane-polarized light (*PPL*) and *right*: crossed-polarized light (*XPL*). Note the *bright red* birefringence due to orientation of clay laminae in XPL. Such pedofeatures have been attributed to human-induced soil disturbances (e.g., cultivation). Vashtëmi, Albania.

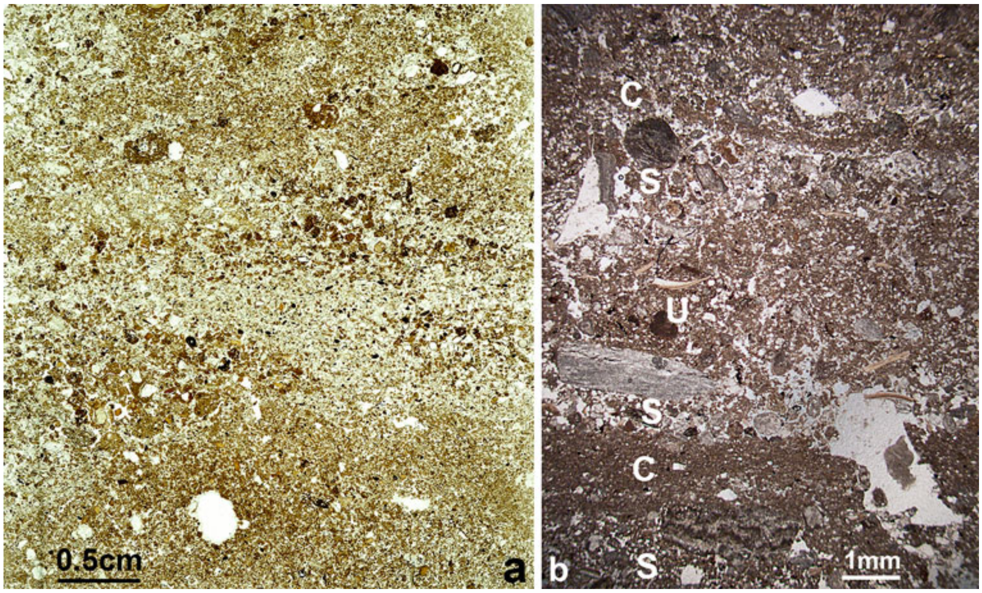
There are several techniques for sampling monoliths, such as cutting blocks of appropriate dimensions using hammer and chisel out of strongly consolidated sediments or carving blocks using a sharp knife in relatively firm sediment, or applying plaster of Paris or gypsum cloth to the surface of blocks carved from loose stony sediments (Figure 1) (Goldberg and Macphail, 2003). The dimensions of the sampled blocks vary according to the type of sediment, the stratigraphy of the site, the aim of the analysis, and the size of the finished thin section. Although monoliths of 15 × 15 × 40 cm are commonly collected, 10 × 10 × 15 cm-size blocks are more typical. It also follows that the stratigraphy of the site will dictate the number and location of samples and if the sampling will be systematic or selective. The samples are oven-dried at 50 °C for several days and then impregnated – under vacuum if a large enough chamber exists – with polyester resin diluted with styrene or acetone. Finally, petrographic thin sections of various large formats (7 × 5 cm up to 8 × 15 cm) are prepared.

The finished thin sections are studied with stereomicroscopes and petrographic microscopes at magnifications ranging from 1 to 500×. It is best to examine the thin sections first over a large area with a stereomicroscope, which permits observation of the nature of peds (natural soil particulate aggregates) in soils and the geometry of some relatively large features often encountered in archaeological deposits. Indeed, several of the patterns of arrangement of microscopic elements are best observed with a stereomicroscope or by observation of high-resolution scans of the thin sections (Arpin et al., 2002). Polished slabs of the blocks should also be examined before the thin sections are studied for the same reason. In addition, the same thin sections or polished parts of them can be studied using an SEM to magnifications of several thousand times; at the same time, selected spots can be analyzed chemically for their elemental content with electron microprobe techniques.

One of the main limitations of micromorphology in archaeology is the representation of results (see, e.g., Weiner, 2010, 74). The size of a thin section is relatively small in relation to the distribution of relevant variations observed in the sampled unit, and therefore the scale of these variations should also influence the sampling strategy. However, field observation is a prerequisite of good micromorphology, so the best sampling strategy is to establish while in the field the main facies that constitute the stratigraphy. The number and types of facies will determine the number of samples and the type of sampling. Microscopic examination of the main facies types eventually will lead to the creation of sub-facies, and in this way a refinement of the original sampling strategy will follow. As has been summarized by Courty (2001, Figure 8.3), a long-term iterative field/laboratory strategy provides the best representation of materials for interpretation.

Micromorphological analysis

Under the microscope, the coarser grains (sand size and larger) are examined for mineral and organic composition, abundance, size, shape, and distribution. The finer matrix material (silt and clay) can be observed only with respect to its internal organization, which is expressed under crossed-polarized light by interference colors and birefringence. For instance, clay particles in fine textured sediments are horizontally oriented as a result of gradual settling, and this orientation displays birefringence orientation in the form of parallel extinction when observed in thin section between crossed polarizers (Figure 2).



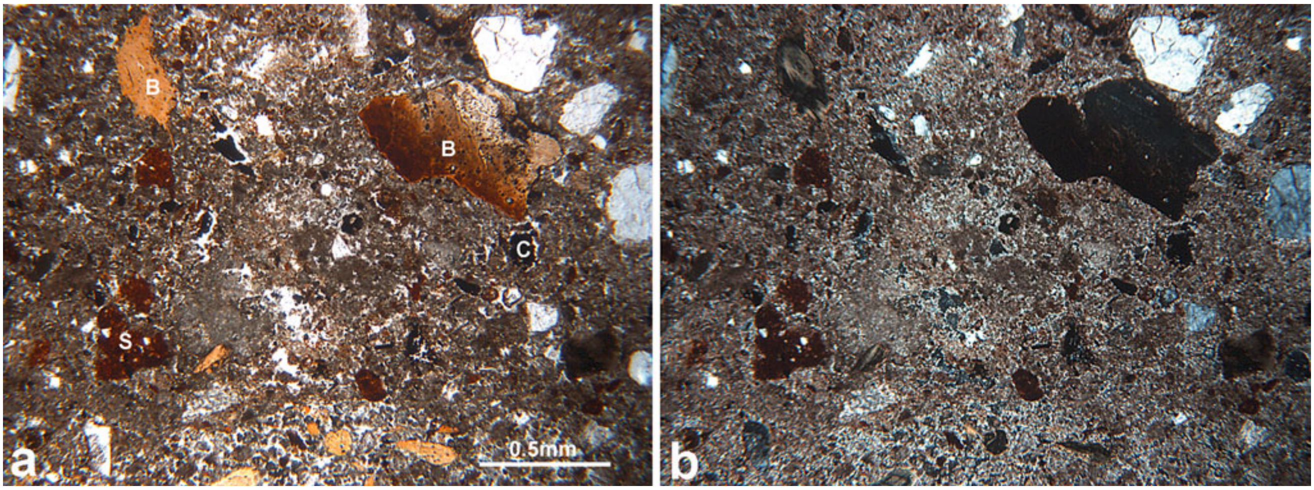
Soil Micromorphology, Figure 3 Examples of shallow sheet wash sediments: (**a**) Macroscan of a thin section showing laminae of well-sorted silt and sand inside crudely sorted fine-grained sediment. The sand fraction consists of single grain and aggregated material. Theopetra Cave, Greece. (**b**) Interbedded clay silt laminae (*C*), moderately sorted single-grained sand (*S*), and unsorted sandy-silt clay (*U*). Grading is observed in the lower part. PPL, Makri, Greece.

At a higher level of order is the fabric, which describes the total organization of the constituents described above, including their spatial arrangement, shape, size, and frequency of occurrence. Features that reflect the history of the material can be grouped into three types:

1. *Sedimentary features* relate to the source of sediments, mode of transport, deposition of clastic grains, or chemical accumulations. Deposition produces sedimentary structures, which are the direct manifestation of the depositing medium (air or various types of fluid) and energy conditions prevalent at the time of deposition (Reineck and Singh 1980, 8). They include all the bedding and surface features produced during sediment deposition (Figures 3 and 4).
2. *Pedologic and postdepositional features* refer to modifications of existing materials by biological, mechanical, or chemical processes. Examples include clay coatings (in voids and around grains or aggregates), excrements, and precipitation of carbonates or oxides resulting in the formation of nodules and mottles (Figure 2).
3. *Anthropogenic features* result from human activities and are manifested mainly by ashes, charcoal, bone, organic matter, lithics and pottery, and construction materials (Figures 5, 6, and 7).

Soil Micromorphology, Figure 4 Photomicrograph of sedimentary crusts (PPL). Each crust has a coarse texture at the bottom and grades upward to finer material. Kolona, Aegina, Greece.

The modern terminology of soil micromorphology is largely descriptive (Bullock et al., 1985; Stoops, 2003) and commonly uses similar descriptive approaches found in sedimentology. This objective terminological approach is unlike the heavily genetic one first conceptualized by Brewer (1964), which was designed for the needs of describing soils. As such, it is quite unsuited to describing



Soil Micromorphology, Figure 5 Photomicrograph of burnt remains, (**a**) in PPL and (**b**) in XPL, showing burnt bone (*B*), charcoal (*C*), and oxidized burnt soil aggregates (*S*) inside a *dark gray* (in PPL) calcitic mass consisting of ash crystals with dotted appearance (in XPL) that have begun to recrystallize (*light grey* areas in XPL). Lakonis Cave, Greece.

sediments or even the sedimentary aspects of soils. The textbook on soil micromorphology in archaeology by Courty et al. (1989) used a more balanced approach, however, and more recent publications also use terms derived from sedimentary petrography and even from metamorphic petrology (Phillips et al., 2011).

Micromorphology and other techniques

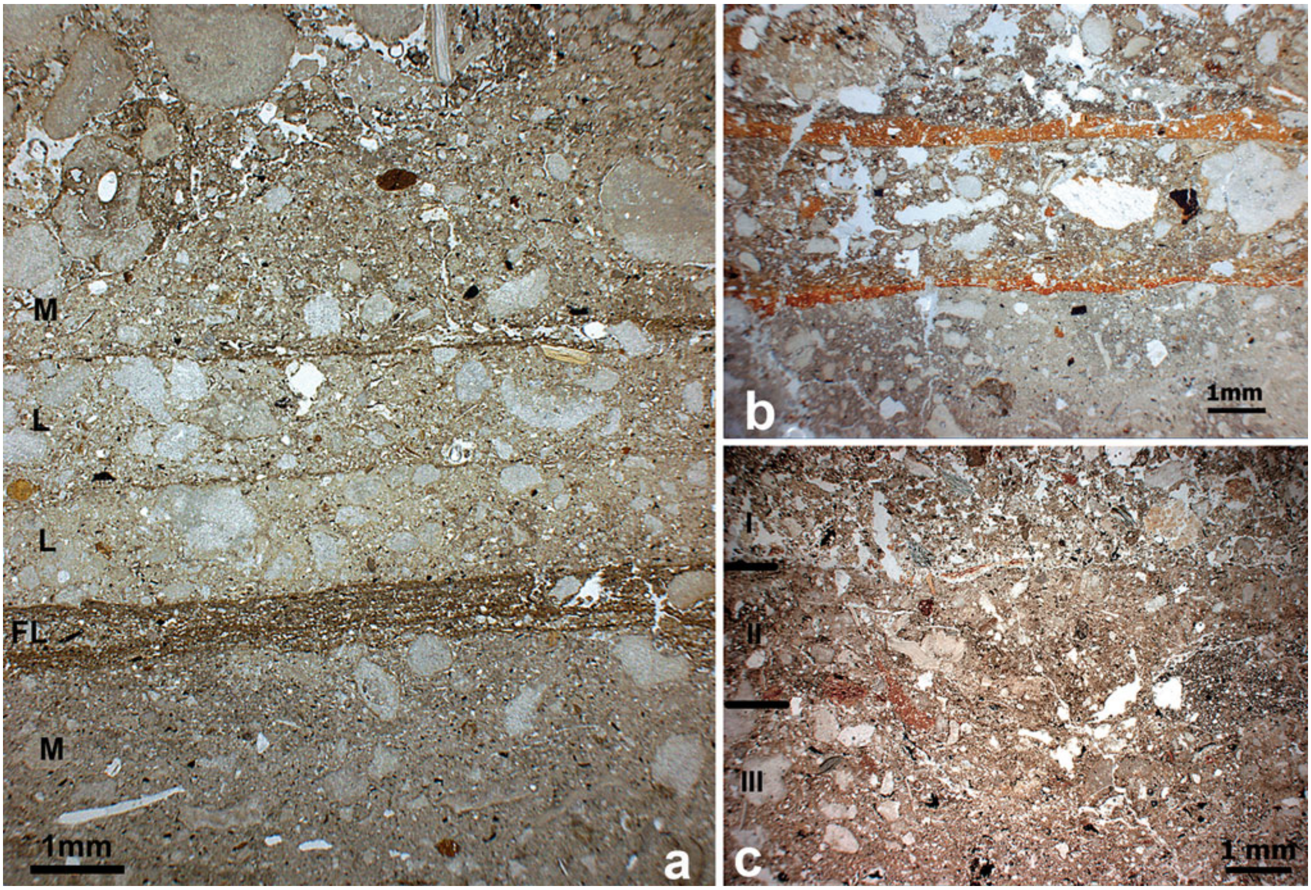
Micromorphology is often combined with other instrumental techniques to further decipher the nature of non-recognizable microscopic features. For example, the nature and origin of amorphous phosphate features in archaeological deposits have been recognized through synchrotron X-ray scattering analysis of thin sections (Adderley et al., 2006) or microprobe analysis (Karkanas et al., 1999; Macphail and Goldberg, 2000). Furthermore, there are several examples where data derived from other disciplines have been integrated with those of micromorphology to provide a more holistic interpretation of site formation processes (e.g., phytolith analysis (Albert et al., 2008), isotopic analysis (Shahack-Gross and Finkelstein, 2008; see also Weiner, 2010). However, it is important to know how the objects under analysis are organized within the sediment. For example, spores and seeds recovered from bulk, homogenized samples cannot inform us as to whether they come from layers associated with stabling remains or with burnt remains, even though they themselves are not burnt. Thus, we need to know the context of these remains, for without it, the interpretation is not only incomplete but could be erroneous. It is thus the thin section of the intact deposits that can provide the context of these organic remains.

A common strategy involves systematic geological sampling of the profiles whereby sedimentological analysis of bulk samples yields quantitative information. Bulk samples are taken back to the laboratory where a variety of analytical methods are used, such as grain-size analysis, clay and heavy mineral determination, phosphate content, organic matter and acidity, carbonates, iron content, and magnetic susceptibility among others. Although some of these methods can provide valuable information on strictly naturally deposited layers, they are of limited value in studying cultural deposits. We cannot interpret excavated earth by treating it as bulk material, because there is no possibility of unraveling the compound effects of two successive events superimposed on the same material, and we cannot differentiate between materials that produce the same analytical measurements (Courty et al., 1989). For example, wood ash and calcareous pedogenic features consist of the same mineral, calcite. Wood ash can be recrystallized to produce indurated features resembling cemented calcareous silt sediments (Karkanas et al., 2007; Figure 5).

A more recent advance in micromorphology is the use of image analysis techniques (Goldberg and Whitbread, 1993; Adderley et al., 2006). Processed images are used to identify pores, grains, and dark (organic) material and to measure area, number or frequency, and shape and size parameters of objects and voids. One way of using image analysis is to compare features like void space between different microfacies or to enhance the visibility of subtle fabrics like deformation features. Quantification measurements provide a more secure basis for interpretation, but as Goldberg and Macphail (2006) acutely notice, researchers must know exactly what they are counting.

Applications

The analysis of microstratigraphy and microstructure of archaeological sequences as well as the examination of



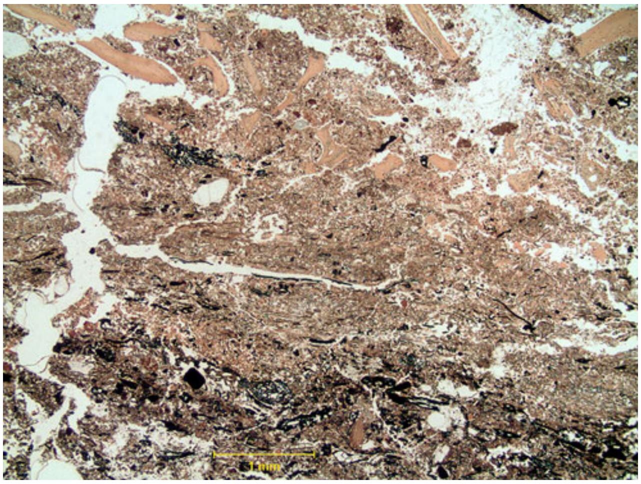
Soil Micromorphology, Figure 6 Photomicrographs of plaster floors with characteristic dense mosaic fabric. The overall homogeneity is correlated with the degree of processing of the material in antiquity. (**a**) Pure lime replastering (L) between impure lime floors (M). Note the dusty appearance of the lower floor due to the large amounts of finely dispersed, flaky charcoal and ash inclusions. All surfaces are covered by dark organic-rich microstratified debris. The lower one (FL) is much better developed, consisting of finely laminated decayed organic matter interbedded with coarser sediment having a dense mosaic fabric. (**b**) Red clay finishing coats on well-prepared lime floors. The upper one was laid on a replastering surface. (**c**) Surface of a poorly prepared floor enriched in lime (II) relative to its clay-rich substrate (III). The overlying material is loose, mostly ashy debris (I). Note also the general dirty appearance of the floor and the occurrence of some vughs. PPL, Makri, Greece.

relationships among construction features, sediments, and their archaeological findings has been employed successfully to interpret natural depositional processes and paleoenvironmental changes, human-induced soil formations and disturbances, land management, the use of space, and the structure of sites.

Human-induced soil formations and disturbances

One of the earliest applications of soil micromorphology in archaeology was the study of soil development throughout the Holocene and how humans have affected this pedogenesis (Macphail, 1986; Macphail et al., 1987). Early Neolithic cultivation resulted in extensive disturbance of parent soil material. The direct effect of tillage is reworking of the fabric, and, consequently, mobilization and translocation of loose soil material by water and formation of pedofeatures such as dusty clay coatings, void infills, and intercalations (Figure 2) (Macphail et al., 1987). Eventually, such processes led to the depletion of soil nutrients and the formation of acid soils (podzolization). In northern European countries, the woodland cover was succeeded by poor heath lands caused by clearance, burning, and cultivation or grazing (for a review see Goldberg and Macphail, 2006, 193–210).

Land management practices in the past, like manuring and disposal of urban waste in arable lands, have been successfully recognized with soil micromorphology (Davidson and Carter, 1998; Adderley et al., 2006). Evidence of manuring may include higher amounts of organic fragments with compositions indicating that they are derived from humic layers, animal dung, or hearth ashes. This activity may lead to overthickened homogeneous



Soil Micromorphology, Figure 7 A photomicrograph from Sibudu Cave, South Africa, showing the contact between laminated organic matter and charcoal at the base, and a weakly bedded phytolith layer above it; trampled bone at the top occurs in a partly disaggregated phytolith-rich layer. PPL.

dark gray upper soil horizons known as plaggen soils (Courty et al., 1989, 134). Such material may later be used in site constructions, which can be readily seen in thin sections (Simpson et al., 2006).

Micromorphological data on cultivation practices have to be treated with caution, however, because other processes can also produce features suggestive of cultivation. Goldberg and Macphail (2006, 203) suggest that all human and environmental factors have to be taken into consideration when studying cultivated soils. Furthermore, such micromorphological studies are often supplemented by other methods and techniques like pollen, chemical, grain-size, and image analysis, which provide additional evidence on cultivation and manuring.

Natural processes in archaeological sites

In archaeological sites, natural formation processes contribute significantly to the accumulation of sediment and to the preservation or destruction of archaeological patterns. Aeolian, colluvial, high-energy, or low-energy water flow features are easily identified by micromorphology, even when they occur as mm-thick layers inside a predominantly anthropogenic deposit. Fine-scale grading, crude sorting, and orientation of particles are revealed through the microscope (Figures 3 and 4). Each of these features can be attributed to a particular natural sedimentation process, and thus the depositional regime can be identified (Courty et al., 1989). For instance, lenses of laminated and well-sorted increments of juxtaposed mineral sand and well-rounded sand-sized soil aggregates are common inside generally massive fine-grained sediment (Figure 3; Karkanas, 2001; Goldberg et al., 2007). They are related to flow events with relatively moderate to high sediment concentration, such as shallow sheet wash (overland flow) along sloping surfaces, where poor separation of bedload and suspended particles is expected (cf. Bertran and Texier, 1999). Microscopically stratified deposits with angular clasts showing inclined, preferred orientations parallel to the slope and floating in a dense, finer, poorly sorted, sandy-silt matrix are interpreted as flow of liquefied sediments (Karkanas and Goldberg, 2010). In urban sites, sedimentary crusts are among the most secure evidence for the identification of outdoor facies (Matthews, 1995). They consist of alternating fine- and coarse-grained laminae with evidence of grading (Figure 4). They can also be associated with vesicles and horizontal planar voids.

Construction materials

Various construction materials include natural soil or sediments and manufactured materials (Macphail and Goldberg, 2010, and references therein). Natural sediments and soils can be in their raw state or mixed with mineral and plant tempers to produce daub, mud brick, floors, walls, roofs, and other constructions. Anthropogenic sediments like ash, charcoal, dung, bone, and organic refuse have been used in varying proportions in construction materials (Milek and French, 2007). When the context is not clear, or when constructions have decayed or been reworked, their identification is not easy. Micromorphology can aid us to identify these materials, which are usually anomalous, exotic, or characterized by unique features (e.g., straw imprints) and can place the associated archaeological findings in the right context. Furthermore, deciphering the techniques used for producing these materials may lead to inferences on craft specialization and cultural interchange (Goren and Goldberg, 1991; Karkanas, 2007).

Most construction materials are characterized by microscopic features that reflect intentional human preparation. Dense mixing of constituents in the wet state produces a characteristic mosaic fabric where coarser components are embedded in a dense fine groundmass. The overall microscopic appearance, however, can be quite homogeneous because of even distribution of all clast sizes (Figure 6). Furthermore, puddling and working of material in a semi-plastic state can produce domains with oriented fabrics, silty or clayey intercalations, vughs, and vesicles (Macphail and Goldberg, 2010). Adding of plant temper is also characteristic of some construction materials like mud bricks and daub (Courty et al., 1989, 119–120). Tubular-shaped voids that are pseudomorphs of the plant temper are readily observed in thin sections. Lime plasters and mortars are characterized by a dense recrystallized fine calcitic matrix with partially burnt carbonized lime lumps that are well welded in the groundmass (Figure 6; Karkanas, 2007).

It has to be stressed that in all cases, differentiation between types of construction materials is site specific. For instance, mud bricks, daub, and clay floors can be very similar. In each site, the best-preserved constructions have to be studied as a reference, and the sampling strategy should focus upon establishing the sequential decay of all types of construction material (Goldberg, 1979; Friesem et al., 2011). At the same time, the geometry and spatial distribution of the decayed construction features in the field have to be taken into consideration in addition to the micromorphological results in order to identify the original construction type.

Use of space

Different human activities can be clearly demonstrated from the content and fabric of the sediments themselves. In prehistoric, non-constructed sites, cultural deposits are commonly burnt (Figure 5). In the Paleolithic site of Kebara Cave, Israel, distinct types of fire-related features have been identified together with remains of in situ burning as well as sediments that were dumped or moved aside in the process of cleaning and modifying living areas (Goldberg et al., 2007; Meignen et al., 2007). Burning features in undisturbed, primary context are characterized by a bright red (rubified), clay-rich substrate overlain by a black, thin, charcoal-rich layer and an often thicker, bedded, whitish ashy layer with burnt bone and red soil (rubified) inclusions. Microscopically, pristine ash consists of calcite pseudomorphs after plant structures (Wattez and Courty, 1987; Canti, 2003). The composition of raked-out hearths is similar, but the arrangement of the constituents is totally different. Bone, charcoal, calcareous ashes, and reddened soil can occur in the same stratigraphic unit or can be mixed between stratigraphic units. In addition, porosity is elevated. Trampled hearths resemble raked-out hearths, but they are more compacted and thus display reduced porosity (Meignen et al., 2007).

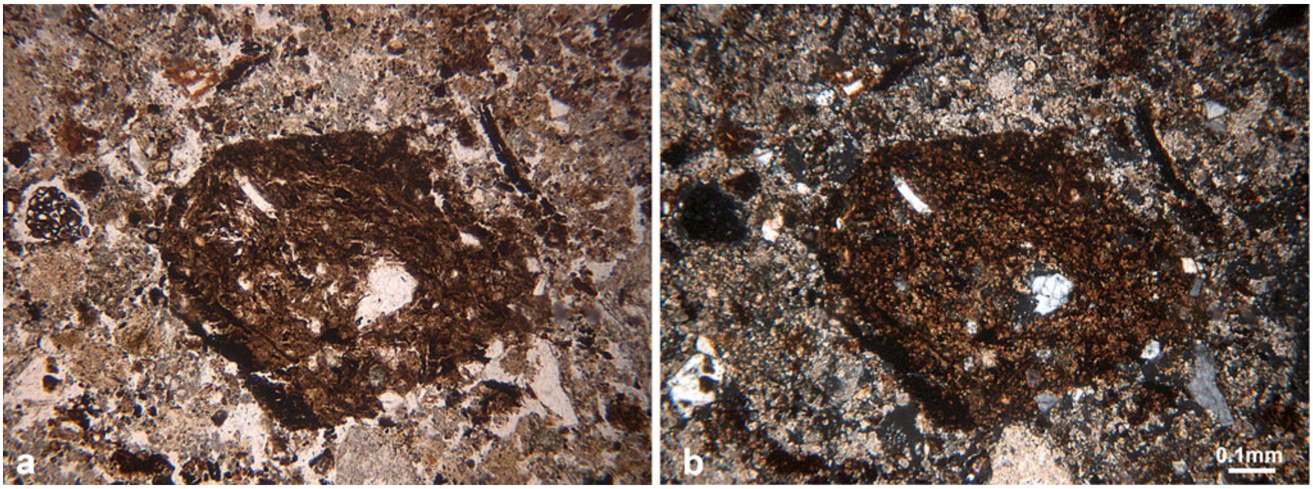
In the Middle Stone Age of Sibudu Cave, South Africa, individual anthropogenic activities were identified, including the construction of hearths and bedding, as well as the maintenance of occupational surfaces through the sweep out of hearths and the repeated burning of bedding. Overlapping series of laminated microfacies were identified, consisting of microlaminated charred or humified organic fibers that often contained stringers of crushed charcoal or phytoliths oriented parallel to the bedding and associated with partially dissolved plant ash (Figure 7). These features were interpreted as intentionally burnt plant material used for surface preparation (bedding) (Goldberg et al., 2009).

In sites characterized by human constructions, such as tells, detailed micromorphological studies of living floors, their maintenance, and the associated occupational debris have provided clues to the use of space at the site (Matthews, 1995; Matthews et al., 1994; Shahack-Gross et al., 2005; Karkanas and Efstratiou, 2009) as well as insights into pyrotechnological activities (Berna et al., 2007). Spatial and contextual variation in the type, thickness, and frequency of plaster floors and occupational deposits within and between buildings has been attributed to different uses of space (Matthews et al., 1996). In Neolithic Makri, Greece, it was noted that a series of well-prepared lime-plastered floors reoccurred at relatively regular intervals over large areas of the settlement (Karkanas and Efstratiou, 2009). It was also noted that these floors were kept exceptionally clean, that they often preserve a finishing coat of red clay or laminated debris of dusty, dark organic-rich material (Figure 6), and that, rarely, a lamina of articulated phytoliths is recovered that may represent decayed organic matting (cf. Gé et al., 1993; Matthews, 1995). Between these well-prepared lime floors, layers of overlapping and randomly recurring, poorly prepared floors were identified. The top of some of these layers occasionally preserved smooth slaked surfaces, enriched in lime, that resulted from final finishing of the top of a floor or lime replastering (Figure 6c). In addition, it was possible to define microlaminated organic-rich debris on top of some of the compacted layers, particularly when these were protected by the construction of a well-prepared floor above (Figure 6a). The identification of such planar structures was a decisive criterion for defining them as in situ floors (see Macphail et al., 2006).

In the investigation of ancient pastoral activities, micromorphology enables us to differentiate between animal species and possibly food sources and grazing processes on the basis of differences in the nature of the components as well as the structure and arrangement of dung remains (Figure 8) (Courty et al., 1991; Boschian and Montagnari-Kokelj, 2000; Macphail et al., 1997; Karkanas, 2006). Further progress in the understanding of stabling deposits was made by characterizing soil microfabrics formed in contemporary abandoned pastoral sites (Shahack-Gross et al., 2003, 2004). The Neolithic cave of Arene Candide in Liguria, Italy, comprises a sequence of gray, homogeneous, and stratified sediments (Macphail et al., 1997). Detailed micromorphological analysis indicates that the cave was used both for herbivore stabling and for domestic occupation. The dung layers consist of a basal, phosphate-rich, stained sub-layer of mainly uncharred plant material. This sub-layer is overlain by ashed and semi-ashed material with burnt, coarse convolute fragments of sheep and goat coprolites and finally by wood ashes. This sequence suggests that the stabling remains were frequently burnt most likely for cleaning purposes. The homogeneous sequence represents mainly domestic occupational deposits that consist of multiple layered, articulated phytoliths and plant tissues used for domestic bedding and thin red soil layers with indications of processing in a wet state. The spatial and temporal organization of domestic occupation and herbivore stabling enabled an interpretation of the changes in cave use during the Neolithic.

Postdepositional alterations

Sediments are affected by a large variety of physical and chemical transformations after they have been deposited. From both sedimentological and archaeological



Soil Micromorphology, Figure 8 Photomicrographs (**a**) PPL and (**b**) XPL of a slightly charred ovicaprine dung fragment inside loosely aggregated sediment consisting mainly of calcitic ashes. Bright spots in the dung shown in XPL are dung spherulites (silt-sized, ~5–15 μm calcareous spheres with a pseudo-uniaxial interference under crossed-polarized light; see Shahack-Gross et al., 2004). Kouveleiki Cave, Greece.

perspectives, pedogenesis can also be included in postdepositional alterations (Courty et al., 1989). Physical, chemical, or biological processes produce certain features that are recognizable in thin sections. Each kind of microfauna produces excrements of specific shape and sometimes size (Bullock et al., 1985). Movement of materials through the sediment or soil produces microscopic textural features like void coatings and infillings (Stoops, 2003). Crosscutting relationships between these micromorphological features provide evidence for the sequence of mineral development in soils. Moreover, minerals in the process of alteration document the progress of chemical reactions (Karkanas, 2010). Analysis of all these processes contributes significantly to understanding paleoenvironmental conditions and provides insights into the completeness of the archaeological record.

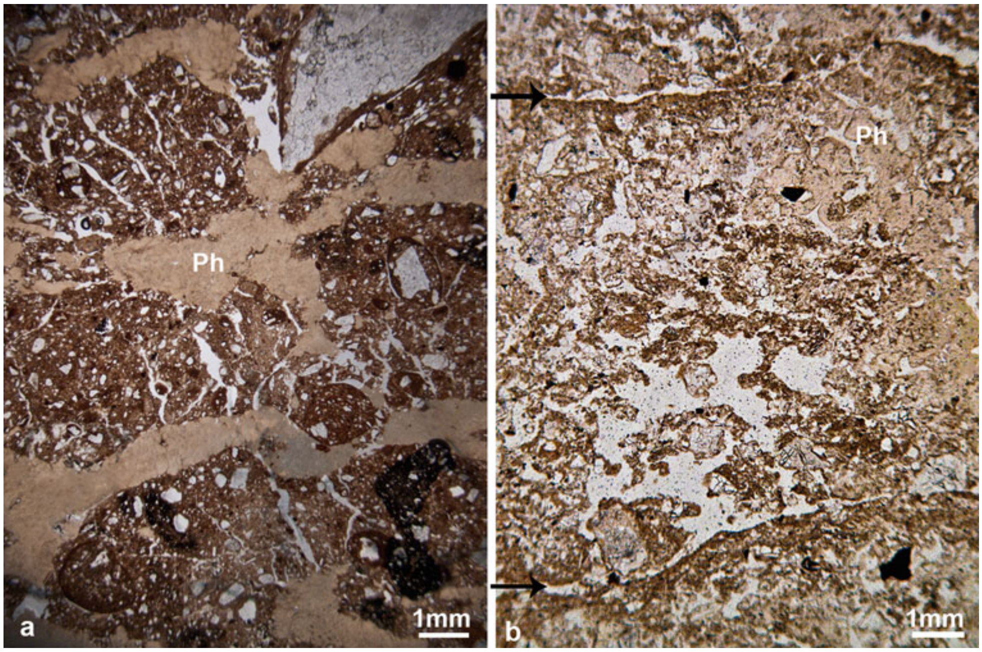
Commonly, archaeological deposits of Pleistocene age are affected by cryogenic processes. Evidence of freezing in sediments is revealed by a characteristic platy and lenticular microstructure (van Vliet Lanoë, 2010). In Theopetra Cave, Greece, freeze-thaw and chemical alteration have acted on the same deposits, producing a complex sequence of postdepositional events (Karkanas, 2001). In some layers, authigenic phosphate minerals fill cryogenic cracks that postdate the freezing event. In other layers, however, phosphatic features are themselves affected by freeze-thaw activity (Figure 9). Therefore, the spatial distribution of microscopic frost features and chemical alteration features permits differentiation of the superimposed cryogenic events and thereby enables a better understanding of the paleoclimatic changes in the area. Moreover, the presence of certain phosphate minerals is associated with the dissolution of bone and alteration of calcareous materials such as wood ash (Karkanas et al., 2000). Instrumental mineralogical and microchemical techniques have been used to identify the mineral phases seen in the thin sections.

In old sites, stratigraphic gaps are not readily identified by field observations due to postdepositional alterations. Identifying and separating the sequence of events that have affected the same sediment is of major importance in reconstructing the depositional history of a site. An example comes from Geißenklösterle Cave, Germany, where micromorphological analysis was able to confirm a major change in the diagenetic regime between the Middle and Upper Paleolithic sequences (Goldberg and Berna, 2010). Middle Paleolithic phosphatized sediments are sharply overlain by unweathered, calcareous Upper Paleolithic sediments. This finding helped to elucidate the nature of the so-called Middle–Upper Paleolithic transition at this particular site and placed finite constraints on what can be said about it.

Summary

Applications of micromorphology in archaeology have witnessed a steady increase over the last 30 years. The microscopic study of soils and paleosols within and surrounding archaeological sites continues to provide important information for paleoenvironmental reconstructions and insights into the role of humans in shaping the environment. Human-induced soil formation and disturbances are especially relevant in this respect, and micromorphology provides basic information about how soils are constructed and how they develop.

The application of micromorphology to the study of site formation processes has proved to be a very powerful tool in placing archaeological findings in their proper context.



Soil Micromorphology, Figure 9 Examples of postdepositional alterations: (**a**) phosphates (*Ph*) filling planar cracks produced by freeze-thaw action; (**b**) frost cracks (*with arrows*) crosscutting phosphate deposits (Ph). PPL, Theopetra Cave, Greece.

Archaeological sites comprise a complex array of natural and anthropogenic processes, and therefore, petrographic and micromorphological methods, including ideas and concepts from different earth science disciplines, should be combined in order to yield the best results. Applying micromorphology to the study of archaeological deposits provides valuable results because the structure and fabric of sediment constituents reflect the forces and agents that deposited them. Organization of the coarser components can be readily seen with the naked eye, but the finer fractions can be seen only under the microscope. The study of archaeological sediments will greatly benefit from observations at all scales.

Bibliography

Adderley, W. P., Simpson, I. A., and Davidson, D. A., 2006. Historic landscape management: a validation of quantitative soil thin-section analyses. *Journal of Archaeological Science*, **33**(3), 320–334.

Albert, R. M., Shahack-Gross, R., Cabanes, D., Gilboa, A., Lev-Yadun, S., Portillo, M., Sharon, I., Boaretto, E., and Weiner, S., 2008. Phytolith-rich layers from the Late Bronze and Iron Ages at Tel Dor (Israel): mode of formation and archaeological significance. *Journal of Archaeological Science*, **35**(1), 57–75.

Arpin, T. L., Mallol, C., and Goldberg, P., 2002. A new method of analyzing and documenting micromorphological thin sections using flatbed scanners: applications in geoarchaeological studies. *Geoarchaeology*, **17**(3), 305–313.

Berna, F., Behar, A., Shahack-Gross, R., Berg, J., Boaretto, E., Gilboa, A., Sharon, I., Shalev, S., Shilstein, S., Yahalom-Mack, N., Zorn, J. R., and Weiner, S., 2007. Sediments exposed to high temperatures: reconstructing pyrotechnological processes in Late Bronze and Iron Age strata at Tel Dor (Israel). *Journal of Archaeological Science*, **34**(3), 358–373.

Bertran, P., and Texier, J.-P., 1999. Facies and microfacies of slope deposits. *Catena*, **35**(2–4), 99–121.

Boschian, G., and Montagnari-Kokelj, E., 2000. Prehistoric shepherds and caves in the Trieste karst (northeastern Italy). *Geoarchaeology*, **15**(4), 331–371.

Brewer, R., 1964. *Fabric and Mineral Analysis of Soils*. New York: Wiley.

Bullock, P., Fedoroff, N., Jongerius, A., Stoops, G., and Tursina, T., 1985. *Handbook for Soil Thin Section Description*. Wolverhampton: Waine Research Publishers.

Canti, M. G., 2003. Aspects of the chemical and microscopic characteristics of plant ashes found in archaeological soils. *Catena*, **54**(3), 339–361.

Cornwall, I. W., 1958. *Soils for the Archaeologist*. London: Phoenix.

Courty, M.-A., 2001. Microfacies analysis assisting archaeological stratigraphy. In Goldberg, P., Holliday, V. T., and Ferring, C. R. (eds.), *Earth Sciences and Archaeology*. New York: Kluwer, pp. 205–239.

Courty, M.-A., Goldberg, P., and Macphail, R. I., 1989. *Soils and Micromorphology in Archaeology*. Cambridge: Cambridge University Press.

Courty, M.-A., Macphail, R. I., and Wattez, J., 1991. Soil micromorphological indicators of pastoralism with special reference to Arene Candide, Fianle Ligure, Italy. *Rivista di Studi Liguri*, **57** (1–4), 127–150.

Davidson, D. A., and Carter, S. P., 1998. Micromorphological evidence of past agricultural practices in cultivated soils: the impact of a traditional agricultural system on soils in Papa Stour, Shetland. *Journal of Archaeological Science*, **25**(9), 827–838.

Díaz, A. P., and Eraso, J. F., 2010. Same anthropogenic activity, different taphonomic processes: a comparison of deposits

from Los Husos I & II (upper Ebro basin, Spain). *Quaternary International*, **214**(1–2), 82–97.
Flügel, E., 2004. *Microfacies of Carbonate Rocks: Analysis, Interpretation and Application*. Berlin: Springer.
Förstner, U., Müller, G., and Reineck, H.-E., 1968. Sedimente und Sedimentfüge des Rheindeltas im Bodensee. *Neues Jahrbuch für Mineralogie (Abhandlungen)*, **109**, 33–62.
Friesem, D., Boaretto, E., Eliyahu-Behar, A., and Shahack-Gross, R., 2011. Degradation of mud brick houses in an arid environment: a geoarchaeological model. *Journal of Archaeological Science*, **38**(5), 1135–1147.
Gé, T., Courty, M.-A., Matthews, W., and Wattez, J., 1993. Sedimentary formation processes of occupation surfaces. In Goldberg, P., Nash, D. T., and Petraglia, M. D. (eds.), *Formation Processes in Archaeological Context*. Madison, WI: Prehistory Press. Monographs in World Archaeology, Vol. 17, pp. 149–163.
Goldberg, P., 1979. Geology of the Late Bronze Age mudbrick from Tel Lachish, Tel Aviv. *Journal of the Tel Aviv Institute of Archaeology*, **6**(1), 60–71.
Goldberg, P., 1980. Micromorphology in archaeology and prehistory. *Paléorient*, **6**(1), 159–164.
Goldberg, P., and Whitbread, I., 1993. Micromorphological study of a Bedouin tent floor. In Goldberg, P., Nash, D. T., and Petraglia, M. D. (eds.), *Formation Processes in Archaeological Context*. Madison, WI: Prehistory Press. Monographs in World Archaeology, Vol. 17, pp. 165–188.
Goldberg, P., and Macphail, R. I., 2003. Strategies and techniques in collecting micromorphology samples. *Geoarchaeology*, **18**(5), 571–578.
Goldberg, P., and Macphail, R. I., 2006. *Practical and Theoretical Geoarchaeology*. Oxford: Blackwell.
Goldberg, P., and Berna, F., 2010. Micromorphology and context. *Quaternary International*, **214**(1–2), 56–62.
Goldberg, P., Laville, H., and Meignen, L., 2007. Stratigraphy and geoarchaeological history of Kebara Cave, Mount Carmel. In Bar-Yosef, O., and Meignen, L. (eds.), *Kebara Cave, Part 1*. Cambridge: Peabody Museum of Archaeology and Ethnology Harvard University, pp. 49–89.
Goldberg, P., Miller, C. E., Schiegl, S., Ligouis, B., Berna, F., Conard, N. J., and Wadley, L., 2009. Bedding, hearths, and site maintenance in the Middle Stone Age of Sibudu Cave, KwaZulu-Natal, South Africa. *Archaeological and Anthropological Sciences*, **1**(2), 95–122.
Goren, Y., and Goldberg, P., 1991. Petrographic thin sections and the development of Neolithic plaster production in northern Israel. *Journal of Field Archaeology*, **18**(1), 131–138.
Karkanas, P., 2001. Site formation processes in Theopetra Cave: a record of climatic change during the Late Pleistocene and early Holocene in Thessaly, Greece. *Geoarchaeology*, **16**(4), 373–399.
Karkanas, P., 2006. Late Neolithic household activities in marginal areas: the micromorphological evidence from the Kouveleiki caves, Peloponnese, Greece. *Journal of Archaeological Science*, **33**(11), 1628–1641.
Karkanas, P., 2007. Identification of lime plaster in prehistory using petrographic methods: a review and reconsideration of the data on the basis of experimental and case studies. *Geoarchaeology*, **22**(7), 775–796.
Karkanas, P., 2010. Preservation of anthropogenic materials under different geochemical processes: a mineralogical approach. *Quaternary International*, **214**(1–2), 63–69.
Karkanas, P., and Efstratiou, N., 2009. Floor sequences in Neolithic Makri, Greece: micromorphology reveals cycles of renovation. *Antiquity*, **83**(322), 955–967.
Karkanas, P., and Goldberg, P., 2010. Site formation processes at Pinnacle Point Cave 13B (Mossel Bay, Western Cape Province, South Africa): resolving stratigraphic and depositional complexities with micromorphology. *Journal of Human Evolution*, **59** (3–4), 256–273.
Karkanas, P., Kyparissi-Apostolika, N., Bar-Yosef, O., and Weiner, S., 1999. Mineral assemblages in Theopetra, Greece: a framework for understanding diagenesis in a prehistoric cave. *Journal of Archaeological Science*, **26**(9), 1171–1180.
Karkanas, P., Bar-Yosef, O., Goldberg, P., and Weiner, S., 2000. Diagenesis in prehistoric caves: the use of minerals that form in situ to assess the completeness of the archaeological record. *Journal of Archaeological Science*, **27**(10), 915–929.
Karkanas, P., Shahack-Gross, R., Ayalon, A., Bar-Matthews, M., Barkai, R., Frumkin, A., Gopher, A., and Stiner, M. C., 2007. Evidence for habitual use of fire at the end of the Lower Paleolithic: site-formation processes at Qesem Cave, Israel. *Journal of Human Evolution*, **53**(2), 197–212.
Karkanas, P., Pavlopoulos, K., Kouli, K., Ntinou, M., Tsartsidou, G., Facorellis, Y., and Tsourou, T., 2011. Palaeoenvironments and site formation processes at the Neolithic lakeside settlement of Dispilio, Kastoria, northern Greece. *Geoarchaeology*, **26**(1), 83–117.
Kourampas, N., Simpson, I. A., Perera, N., Deraniyagala, S. U., and Wijeyapala, W. H., 2009. Rockshelter sedimentation in a dynamic tropical landscape: Late Pleistocene-early Holocene archaeological deposits in Kitulgala Beli-Lena, southwestern Sri Lanka. *Geoarchaeology*, **24**(6), 677–714.
Kubiëna, W. L., 1938. *Micropedology*. Ames, IA: Collegiate Press.
Kuehl, S. A., Nittrouer, C. A., and DeMaster, D. J., 1988. Microfabric study of fine-grained sediments; observations from the Amazon subaqueous delta. *Journal of Sedimentary Research*, **58**(1), 12–23.
Kuehl, S. A., Hariu, T. M., Sanford, M. W., Nittrouer, C. A., and DeMaster, D. J., 1991. Millimeter-scale sedimentary structure of fine-grained sediments: examples from continental margin environments. In Bennett, R. H., Bryant, W. R., and Hulbert, M. H. (eds.), *Microstructure of Fine-Grained Sediments. From Mud to Shale*. New York: Springer-Verlag, pp. 33–45.
Macphail, R. I., 1986. Paleosols in archaeology: their role in understanding Flandrian pedogenesis. In Wright, V. P. (ed.), *Paleosols: Their Recognition and Interpretation*. Oxford: Blackwell Scientific Publications, pp. 263–290.
Macphail, R. I., and Goldberg, P., 2000. Geoarchaeological investigation of sediments from Gorham's and Vanguard Caves, Gibraltar: microstratigraphical (soil micromorphological and chemical) signatures. In Stringer, C. B., Barton, R. N. E., and Finlayson, J. C. (eds.), *Neanderthals on the Edge*. Oxford: Oxbow Books, pp. 183–200.
Macphail, R. I., and Goldberg, P., 2010. Archaeological materials. In Stoops, G., Marcelino, V., and Mees, F. (eds.), *Interpretation of Micromorphological Features of Soils and Regoliths*. Amsterdam: Elsevier, pp. 589–622.
Macphail, R. I., Romans, J. C. C., and Robertson, L., 1987. The application of micromorphology to the understanding of Holocene soil development in the British Isles, with special reference to early cultivation. In Fedoroff, N., Bresson, L.-M., and Courty, M.-A. (eds.), *Micromorphologie des sols; Actes de la VIIe Ré union internationale de micromorphologie des sols, Paris, juillet 1985*. Paris: Association Française pour l'Étude du Sol, pp. 647–656.
Macphail, R. I., Courty, M.-A., Hather, J., and Wattez, J., 1997. The soil micromorphological evidence of domestic occupation and stabling activities. In Maggi, R. (ed.), *Arene Candide: A Functional and Environmental Assessment of the Holocene Sequence (Excavations Bernabò Brea-Cardini 1940–50)*. Roma: Memorie dell'Istituto Italiano di Paleontologia Umana, Nuova serie 5, pp. 53–88.

Macphail, R. I., Cruise, G. M., Allen, M. J., Linderholm, J., and Reynolds, P., 2004. Archaeological soil and pollen analysis of experimental floor deposits; with special reference to Butser Ancient Farm, Hampshire, UK. *Journal of Archaeological Science*, **31**(2), 175–191.

Macphail, R. I., Linderholm, J., and Karlsson, N., 2006. Scanian pithouses; interpreting fills of grubenhäuser: examples from England and Sweden. In Engelmark, R., and Linderholm, J. (eds.), *Proceedings from the VIII Nordic Conference on the Application of Scientific Methods in Archaeology, Umeå 2001*. University of Umeå, Archaeology and Environment 21, pp. 119–127.

Matthews, W., 1995. Micromorphological characterization and interpretation of occupation deposits and microstratigraphic sequences at Abu Salabikh, Southern Iraq. In Barham, A. J., and Macphail, R. I. (eds.), *Archaeological Sediments and Soils: Analysis, Interpretation and Management*. London: Institute of Archaeology, University College, pp. 41–74.

Matthews, W., Postgate, J. N., Payne, S., Charles, M. P., and Dobney, K., 1994. The imprint of living in an early Mesopotamian city: questions and answers. In Luff, R. -M., and Rowley-Conway, P. (eds), *Whither Environmental Archaeology?* Oxford: Oxbow Monograph 38, pp. 171–212.

Matthews, W., French, C. A. I., Lawrence, T., and Cutler, D., 1996. Multiple surfaces: the micromorphology. In Hodder, I. (ed.), *On the Surface: Catalhöyük 1993–95*. Cambridge: The MacDonald Institute for Research and British Institute of Archaeology of Ankara, pp. 301–342.

Meignen, L., Goldberg, P., and Bar-Yosef, O., 2007. The hearths at Kebara Cave and their role in site formation processes. In Bar-Yosef, O., and Meignen, L. (eds.), *Kebara Cave, Mt. Carmel, Israel: The Middle and Upper Paleolithic Archaeology. Part I*. Cambridge, MA: Peabody Museum, Harvard University. American School of Prehistoric Research, Bulletin, Vol. 49, pp. 91–122.

Milek, K. B., and French, C. A. I., 2007. Soils and sediments in the settlement and harbour at Kaupang. In Skre, D. (ed.), *Kaupang in Skiringssal*. Aarhus: Aarhus University Press, pp. 321–360.

Mücher, H., van Steijn, H., and Kwaad, F., 2010. Colluvial and mass wasting deposits. In Stoops, G., Marcelino, V., and Mees, F. (eds.), *Interpretation of Micromorphological Features of Soils and Regoliths*. Amsterdam: Elsevier, pp. 37–48.

Phillips, E., van der Meer, J. J. M., and Ferguson, A., 2011. A new 'microstructural mapping' methodology for the identification, analysis and interpretation of polyphase deformation within subglacial sediments. *Quaternary Science Reviews*, **30**(19–20), 2570–2596.

Reineck, H.-E., and Singh, I. B., 1980. *Depositional Sedimentary Environments, with Reference to Terrigenous Clastics*. Berlin: Springer-Verlag.

Shahack-Gross, R., and Finkelstein, I., 2008. Subsistence practices in an arid environment: a geoarchaeological investigation in an Iron Age site, the Negev Highlands, Israel. *Journal of Archaeological Science*, **35**(4), 965–982.

Shahack-Gross, R., Marshall, F., and Weiner, S., 2003. Geo-ethnoarchaeology of pastoral sites: the identification of livestock enclosures in abandoned Maasai settlements. *Journal of Archaeological Science*, **30**(4), 439–459.

Shahack-Gross, R., Marshall, F., Ryan, K., and Weiner, S., 2004. Reconstruction of spatial organization in abandoned Maasai settlements: implications for site structure in the pastoral Neolithic of East Africa. *Journal of Archaeological Science*, **31**(10), 1395–1411.

Shahack-Gross, R., Albert, R.-M., Gilboa, A., Nagar-Hilman, O., Sharon, I., and Weiner, S., 2005. Geoarchaeology in an urban context: the uses of space in a Phoenician monumental building at Tel Dor (Israel). *Journal of Archaeological Science*, **32**(9), 1417–1431.

Simpson, I. A., Guttmann, E. B., Cluett, J., and Shepherd, A., 2006. Characterizing anthropic sediments in north European Neolithic settlements: an assessment from Skara Brae, Orkney. *Geoarchaeology*, **21**(3), 221–235.

Stoops, G., 2003. *Guidelines for Analysis and Description of Soil and Regolith Thin Sections*. Madison, WI: Soil Science Society of America.

Van Vliet-Lanoë, B., 2010. Frost action. In Stoops, G., Marcelino, V., and Mees, F. (eds.), *Interpretation of Micromorphological Features of Soils and Regoliths*. Amsterdam: Elsevier, pp. 81–108.

Wattez, J., and Courty, M.-A., 1987. Morphology of ash of some plant materials. In Fedoroff, N., Bresson, L.-M., and Courty, M.-A. (eds.), *Micromorphologie des sols; Actes de la VIIe Ré union internationale de micromorphologie des sols, Paris, juillet 1985*. Paris: Association Française pour l'Étude du Sol, pp. 677–683.

Weiner, S., 2010. *Microarchaeology: Beyond the Visible Archaeological Record*. Cambridge: Cambridge University Press.

Cross-references

Anthrosols
Chemical Alteration
Electron Spin Resonance (ESR) in Archaeological Context
Hearths and Combustion Features
Kebara Cave
Microstratigraphy
Pastoral Sites
Petrography
Scanning Electron Microscopy (SEM)
Site Formation Processes
Soils
Tells

SOIL STRATIGRAPHY

Vance T. Holliday[1], Rolfe D. Mandel[2] and Timothy Beach[3]
[1]Anthropology and Departments Geosciences, University of Arizona, Tucson, AZ, USA
[2]Department of Anthropology, University of Kansas, Lawrence, KS, USA
[3]Department of Geography and the Environment, The University of Texas at Austin, Austin, TX, USA

Introduction

Soil stratigraphy or *pedostratigraphy* is a way of grouping and correlating sediments and rocks based on soil-related, or pedogenic, criteria. This contrasts with *lithostratigraphy* (classification based on lithological characteristics such as color or grain size), chronostratigraphy (classification based on age of deposits or rocks), and *biostratigraphy* (classification based on biological characteristics such as pollen or vertebrate fauna) (see the entry on "Stratigraphy" in this volume). It has been defined as "the study of different soil associations formed in an area during past periods of varied soil-forming conditions" Catt

(1990, 169). Here, the term *association* refers to a group of related soils that vary laterally due to changes in soil-forming factors. This is a more generic use of the term compared to the soil-mapping parlance of the USDA (see the entry on "Soil Survey" in this volume). The unique physical and chemical properties that distinguish soils from sediments make soils quite useful for stratigraphic subdivision and correlation. In particular, pedologic features, most notably soil horizons, are often the most visually prominent features in stratified deposits.

The recognition of soils and their differentiation from sediments in archaeological contexts (discussed below) is one of the most fundamentally significant aspects of geoarchaeological stratigraphy. Because soils indicate periods of stability or hiatuses in deposition (so that the soils have a chance to form), the identification of soils or the lack thereof in a stratigraphic sequence provides information on the number of depositional episodes and intervals of stability. The identification of specific soil horizons also provides clues to the degree and duration of soil development (see the entry on "Soils" in this volume), the nature of the soil-forming environment, and the kinds of soil-forming processes that may impact the archaeological record (see entry on "Site Formation Processes" in this volume).

Soil stratigraphic units have been defined in several ways. They are formally referred to as *pedostratigraphic units* in the North American Stratigraphic Code (NACSN, 2005, 1576–1578). A pedostratigraphic unit is a "buried, traceable, three-dimensional body of rock [or sediment] that consists of one or more differentiated pedologic horizons" developed in and overlain by "one or more formally defined lithostratigraphic or allostratigraphic units" (NACSN, 2005, 1576–1577).

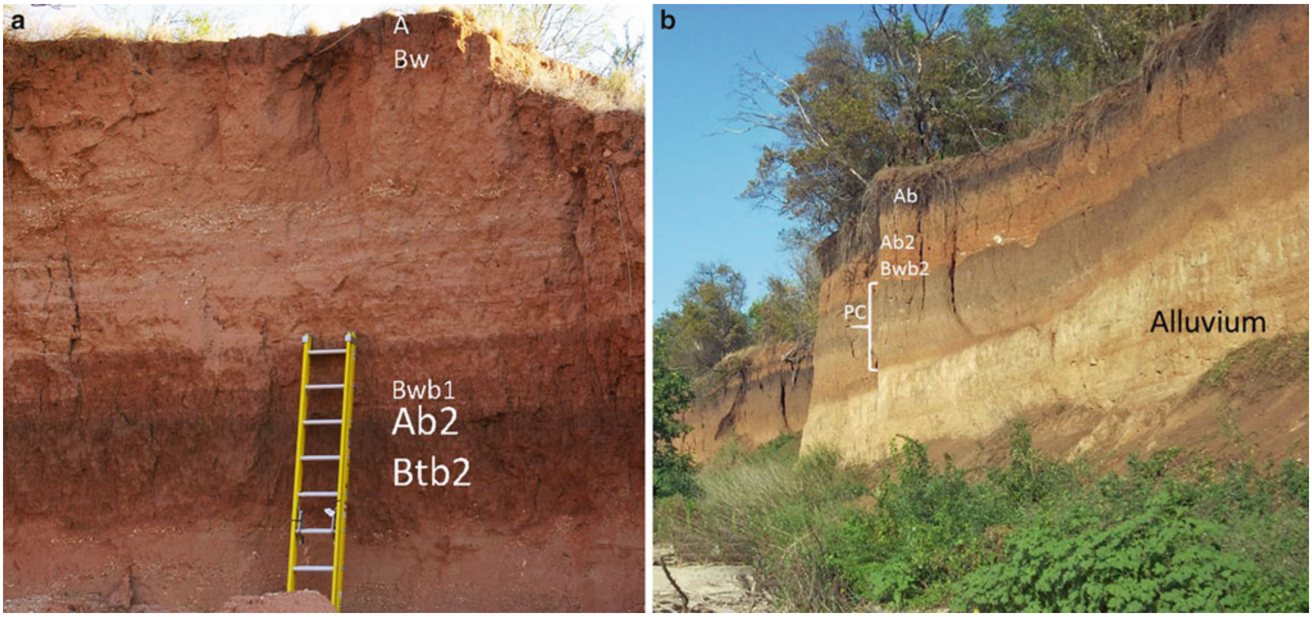
There are several disadvantages to the NACSN definition, particularly in geoarchaeological contexts. The requirement that the soils be buried is illogical and in any case impractical in many field situations. The processes that govern whether or not a soil is buried can be variable and highly localized, particularly in Holocene deposits such as dunes and floodplains where paleosols may be exposed by erosion. The NACSN definition can result in a situation where a clearly traceable soil that is locally buried or exposed is a pedostratigraphic unit in some places but not others. Likewise, the requirement that pedostratigraphic units be developed in and overlain by formally defined stratigraphic units is impractical and unrealistic because formally defined Holocene strata are rare, and formally defined Quaternary units are only locally common. Finally, the NACSN does not indicate how far a buried soil must be traceable for it to be classified as a pedostratigraphic unit. For example, a buried soil that is developed in Holocene alluvium may be traceable in a particular drainage basin or even a small part of a basin, but it may not occur beyond this area. Hence, there may be uncertainty as to whether that soil can be classified as a pedostratigraphic unit.

Several terms have been proposed as the "fundamental unit" of pedostratigraphic classification (i.e., a term equivalent to *formation* as the fundamental unit of lithostratigraphic classification). In the North American Stratigraphic Code, *Geosol* was adopted as the fundamental unit. "Geosol" was chosen over "soil" apparently because of the many different definitions and connotations of "soil," but there is rarely any confusion over the meaning of "soil" among geoarchaeologists, geomorphologists, or Quaternary stratigraphers. Other terms with a connotation more or less similar to Geosol include *groundsurface* (Butler, 1959), *pedolith* (Crook and Coventry, 1967), *pedo-morpholith* (van Dijk et al., 1968), and *pedoderm* (Brewer et al., 1970). Using "soil" to refer to pedostratigraphic units seems the most straightforward approach, however. Ultimately, field investigators should choose the terminology that best suits their situation.

A wide variety of sometimes confusing terminology has been proposed and used to describe the many possible stratigraphic relationships between and within buried soils and soil stratigraphic units. Most of the terms are seldom used, largely because they lack utility in illuminating depositional or landscape history. A review of these terms, however, is a good way to examine them systematically and explain possible stratigraphic relationships among buried soils.

A classical, vertically stacked sequence of buried soils common in many alluvial, colluvial, eolian, and glacial landscapes is a multistory sequence (Figure 1a, b). Closely spaced, multiple buried soils are described by a number of stratigraphic terms. If pedogenic processes from an upper soil extend down into or "overlap" with a lower soil, the process is referred to as soil *welding* and produces a set of *welded soils* (Figure 2) (Ruhe and Olson, 1980). Welded soils are also referred to as *polypedomorphic soils* (Bos and Sevink, 1975; Duchaufour, 1982, 144), *composite soils* (Morrison, 1967, 25, Morrison, 1978, 83–84), and *complex soils* (Bos and Sevink, 1975, 224–225). Soil welding is an important process of post-burial alteration of soils. In Europe, the term *pedocomplex* is often used to describe closely spaced sets of either welded or unwelded soils and also to describe overthickened or cumulic soils (Figure 1b) (see below). In the field, workers will find any combination of welded soils, unwelded soils, pedocomplexes of both, subdivided polygenetic soils, deeply buried soils, and shallowly buried soils. Lateral variation in rates of sedimentation, for example, on a floodplain, can also produce facies between multistory soils, welded soils, and a cumulic soil (Figure 3).

A significant aspect of soil stratigraphic units is that, like surface soils, they vary as the factors that influenced their development (parent material, topography, vegetation, biota, and time) varied. This is a very useful concept in soil



Soil Stratigraphy, Figure 1 Examples of different expressions of buried soils. (**a**) A typical multistory sequence from the headwaters of the Brazos River system on the Rolling Plains of northwest Texas. Below the surface soil and above the first buried soil (Bwb1) is sandy and gravelly alluvium and, immediately above the buried soil, finer muddy alluvium. The soil structure in the A-Btb2 is very well expressed due to high clay content. More sandy and gravelly alluvium is apparent at the base of the section (Photo by Vance T. Holliday). (**b**) Buried soils exposed along the Dnieper River, Ukraine. The Ab-Ab2-Bwb2 multistory sequence and the pedocomplex (*PC*) formed in late Pleistocene loess, but are separated by a distinct erosional unconformity. The PC includes both cumulic and welded soils. The PC rests unconformably on bedded alluvium (Photo by Vance T. Holliday).

stratigraphy because buried soils, like surface soils, can vary laterally. For example, a buried soil that formed in several different parent materials will exhibit different lithological facies. A soil stratigraphic unit that is buried in some places but not in others will exhibit facies variations due to the differences in the age of the soil, i.e., in the amount of time the soil had to form, and possibly due to environmental variations. Soil facies are lateral variations in soils due to variations in one or more of the soil-forming factors (Morrison, 1967, 13, 15; 1978, 86–87).

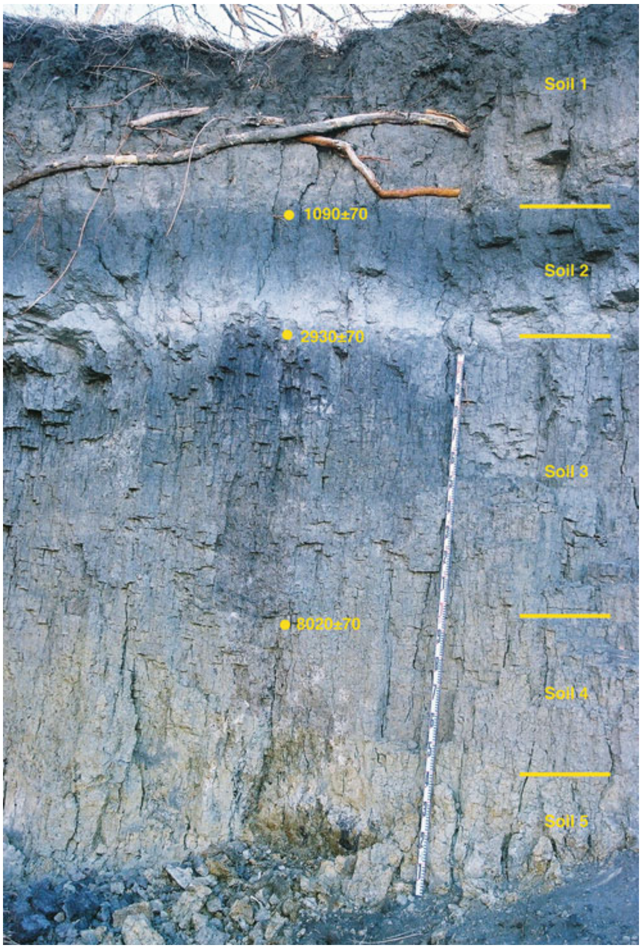
Of particular significance when using soils as age indicators is that buried soils, just like lithostratigraphic units and contemporary surface soils, are diachronic or time transgressive. The age of the upper boundary of the pedostratigraphic unit can vary as the age of the paleo-landsurface associated with the soil varied. Rapid burial over a large area can also produce a buried soil with an isochronous upper boundary (at least within the limits of most dating methods), however.

Variation in a buried soil or soil stratigraphic unit due to variation in the topography and drainage conditions during soil genesis produces a *paleocatena*. Most typically, a paleocatena is simply a buried catena (see entry on "Soils" in this volume). The concept of a buried catena or paleocatena is important because this is a unique aspect of soils relative to other kinds of stratigraphic units and is a key to the recognition of buried soils. Soil stratigraphic units should and do vary just as modern soils at the surface vary today.

Soil stratigraphy versus soil horizonation

The many variables in local and regional soil-forming factors mean that the number and thickness of soil horizons in a soil stratigraphic unit and the position of the lower boundary of the soil can vary significantly. The individual soil horizons and the lower boundary of the soil, therefore, have no stratigraphic significance whatsoever other than to define the soil stratigraphic unit. The lower boundary can be, like the upper one, time transgressive or diachronic. It represents the lowermost significant alteration of the parent material by pedogenic processes.

Soil horizons are not geologic layers; horizons represent an alteration of the layers. The concept of soil horizonation and the specific spatial succession of soil



Soil Stratigraphy, Figure 2 Soil stratigraphy of an alluvial fan exposed in a stream bank along Oak Creek in southeastern Nebraska. Soil 2 has a well-expressed A-E-Bt profile, with the Bt horizon welded to the A horizon of Soil 3 just beneath. In the upper 35 cm of Soil 3, soil welding accounts for the prominent prismatic structure and clay films typical of a Bt horizon, but a dark gray matrix color typical of an A horizon (From Mandel, 2013a: Figure 94).

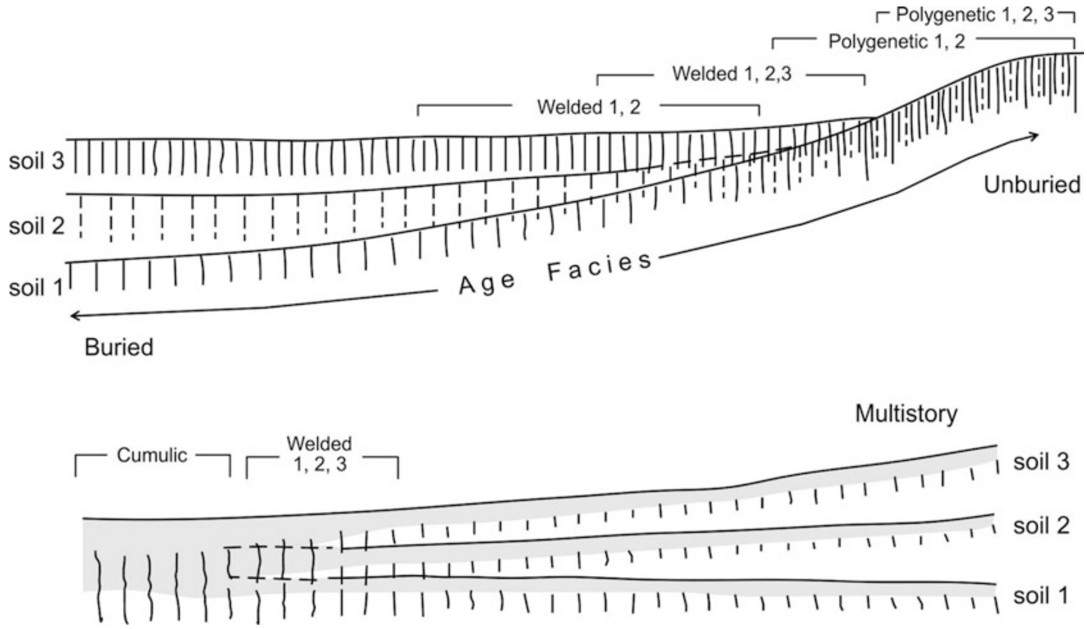
horizons is a significant pedologic paradigm with important stratigraphic ramifications. Soil horizonation extends from the surface downward through the parent material, as a function of pedogenic processes, and thus, individual soil horizons should not be understood as individual stratigraphic entities. Soil horizons are separated in space but are not necessarily separated in time, though some horizons may evolve sequentially after others form (e.g., an A-C profile evolving into an A-Bw-C soil and then into an A-Bt-C sequence) (Figure 4). Moreover, soil horizons, particularly the A, can be thoroughly churned due to the effects of floral and faunal mixing and argilliturbation (see the entry on "Site Formation Processes" in this volume).

Buried soils

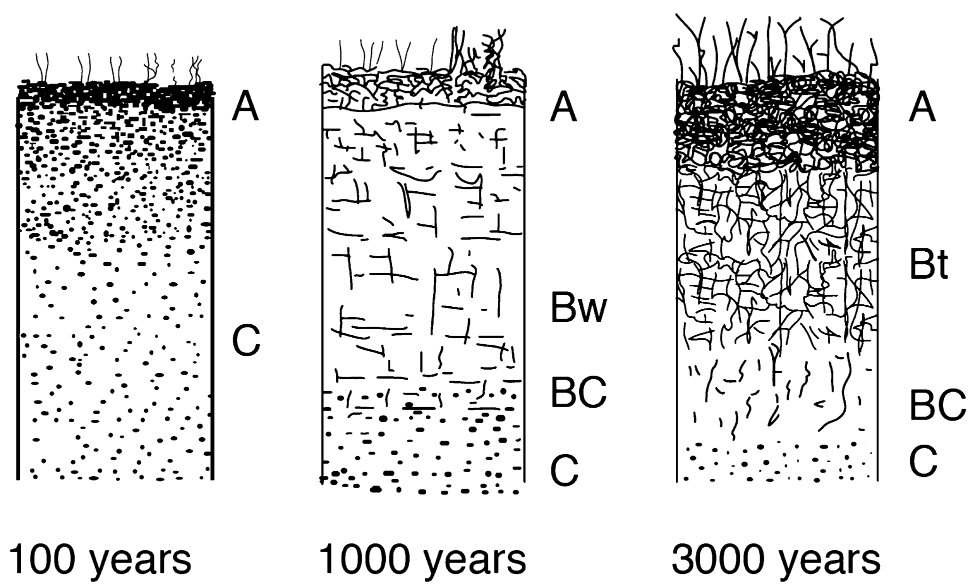
Soil stratigraphy deals with buried soils, which is to say, it deals with buried landscapes. They are three-dimensional bodies, and because soils require some time to form, they can be considered four-dimensional entities. Waters (1992, 82–83) provides a good description of the evolution of strata, one particularly appropriate to the visualization of buried soils (see also Kraus and Brown, 1988; Kraus, 1999; Kraus and Aslan, 1999):

> The nature and structure of a stratigraphic sequence in any environment is determined by the number, timing, areal extent, magnitude, and duration of individual periods of deposition, degradation, and stability.... Over a given interval of time, individual episodes of deposition, stability, and erosion may be of long duration, with changes occurring infrequently, or they may be of short duration and alternate frequently. Furthermore, these episodes may affect a large region or only a small area. Consequently, different. . .sequences of lithostratigraphic units, pedostratigraphic units, and erosional contacts are created.
>
> The total duration of deposition, degradation, and stability determines how much of the time continuum of a stratigraphic sequence is recorded by. . .depositional units (lithostratigraphic units) versus the combined time represented by. . .surfaces of erosion (erosional unconformities) and surfaces of stability (pedostratigraphic units). Episodes of landscape degradation [and/or] stability create gaps in any depositional sequence and thus leave an incomplete geologic record of lithostratigraphic units. The ratio of the total amount of time represented by nondepositional and erosional contacts between lithostratigraphic units produces a measure of the completeness of the stratigraphic sequence.... Generally this ratio is low because the contacts between and within lithostratigraphic units represent the passage of more time than the physical sediments themselves.... (Waters, 1992, 82–83)

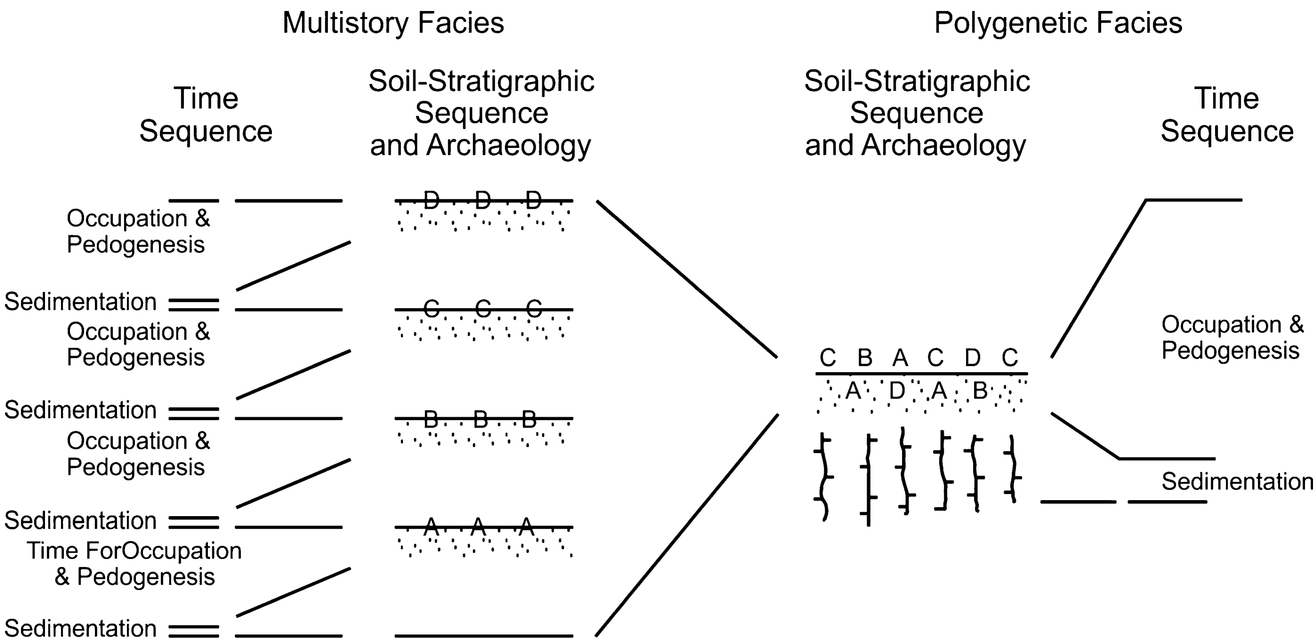
An important point raised in this quote is that soils represent gaps in the sedimentological record – i.e., periods of generally stable landscapes – because there was little or no deposition or erosion. More broadly, recognizing buried soils and establishing soil stratigraphic relationships are important for a wide array of geoarchaeological questions and interpretations. For example, a multistory sequence of weakly expressed buried soils is indicative of rapid sedimentation interrupted by relatively brief periods of stability and soil formation. Such settings could preserve discrete occupation surfaces (Figure 5). On a floodplain, as described above and in Figure 3, this geoarchaeological record could have a facies of a welded, or cumulic, or unburied soil with a mixed or palimpsest archaeological record.



Soil Stratigraphy, Figure 3 Schematic diagrams illustrating the soil stratigraphic and facies relationships of buried, unburied, and cumulic soils and associated terminology. In the *upper* diagram, duration of pedogenesis in the unburied, polygenetic soil is equal to the combined duration of pedogenesis for soils 1, 2, and 3, plus the time of sedimentation (Modified from Holliday (2004: Figure 5.3)).



Soil Stratigraphy, Figure 4 Diagrams showing the hypothetical development of a soil through time, keeping all other soil-forming factors constant. The setting is on the valley floor of a stream in the tallgrass prairie of eastern Kansas, a region with a mean annual rainfall of about 82 cm.



Soil Stratigraphy, Figure 5 Diagram illustrating the impact of varying rates of deposition on the archaeological record. On the *left* side, frequent episodes of flooding and sedimentation produce multistory facies with multiple, weakly expressed soils (indicated by stippling) containing relatively discrete occupation zones (A, B, C, and D), whereas on the *right* side, prolonged stability results in a few polygenetic soils or a single one with a palimpsest or mixing of different occupation debris (Modified from Holliday (2004: Figure 7.2)).

Recognition

Recognition of buried soils depends on (1) the degree of preservation of the soil (which in turn depends on the nature of the burial processes and post-depositional alterations) and (2) the experience of the investigator, including experience working with surface soils and with stratigraphic studies in the given field area. Fundamentally, buried soils can be recognized using the same characteristics used to recognize surface soils (Yaalon, 1971a, 154, 157; Valentine and Dalrymple, 1976, 209–213; Fenwick, 1985, 5–11; Jenkins, 1985; Catt, 1986, 173–174; Catt, 1990, 6–7; Birkeland, 1999, 24–28). In the field, these characteristics include the absence of geologic bedding, recognizable soil horizons, horizons in a typical vertical sequence, typical soil horizon boundaries (sharper upper boundary, more gradual lower boundary), and the formation of stone lines in some environments. Bettis (1992, 129) provides a useful summary of criteria for differentiating soil A horizons from organic-rich alluvium, criteria also applicable to distinguishing other kinds of soil horizons: (1) a gradual or clear lower boundary for A horizons as opposed to an abrupt lower boundary in geologic deposits, (2) absence of bedding in A horizons and its presence in geologic deposits, and (3) the presence of granular or crumb soil structure in A horizons and its absence or weaker development in geologic deposits.

One significant problem in the identification of buried soils is that a number of sedimentary, hydrogeologic, and pedogenic processes can produce zones that look like buried soils (Pyddoke, 1961, 37–39; Tamplin, 1969, 153–154; Brewer, 1972, 332; Rutter, 1978; Catt, 1986, 173; Thorson, 1990, 402–403, 405–406; Ito et al., 1991; Tandon and Kumar, 1999, 131–135; Mandel and Bettis, 2001, 175–180). These processes and deposits include (1) deposition of organic-rich sediment in lacustrine, palustrine, or alluvial settings (which can be confused with A horizons); (2) deposition of red, reddish brown, or brown sediment (which can be confused with Bw or Bt horizons); (3) deposition of clay-rich sediment (which can be confused with Bt horizons); (4) deposition of gray sediment (which can be confused with a redoximorphic horizon); (5) deposition of volcanic ash (which can be confused with Bk or in particular E horizons); (6) illuviation of humus in a Bh or Bhs horizon below a leached, sandy E horizon (which can be confused with an

Soil Stratigraphy, Figure 6 A buried soil with an overthickened Ab horizon developed in late Holocene alluvium at the Alum Creek site (14EW171) in central Kansas. The Ab horizon is 1.2 m thick and contains stratified Middle Ceramic cultural deposits (Modified from Mandel and Bettis, 2001: Figure 7.3).

A horizon buried below unweathered sand); and (7) deposition of calcium carbonate, soluble salts, or iron oxides in lacustrine, palustrine, alluvial, spring, or groundwater settings (which can be confused with Bk, K, By, Bz, or Bs horizons). Post-burial processes such as black, manganese staining and nodule formation also can produce zones that may be mistaken for soil horizons.

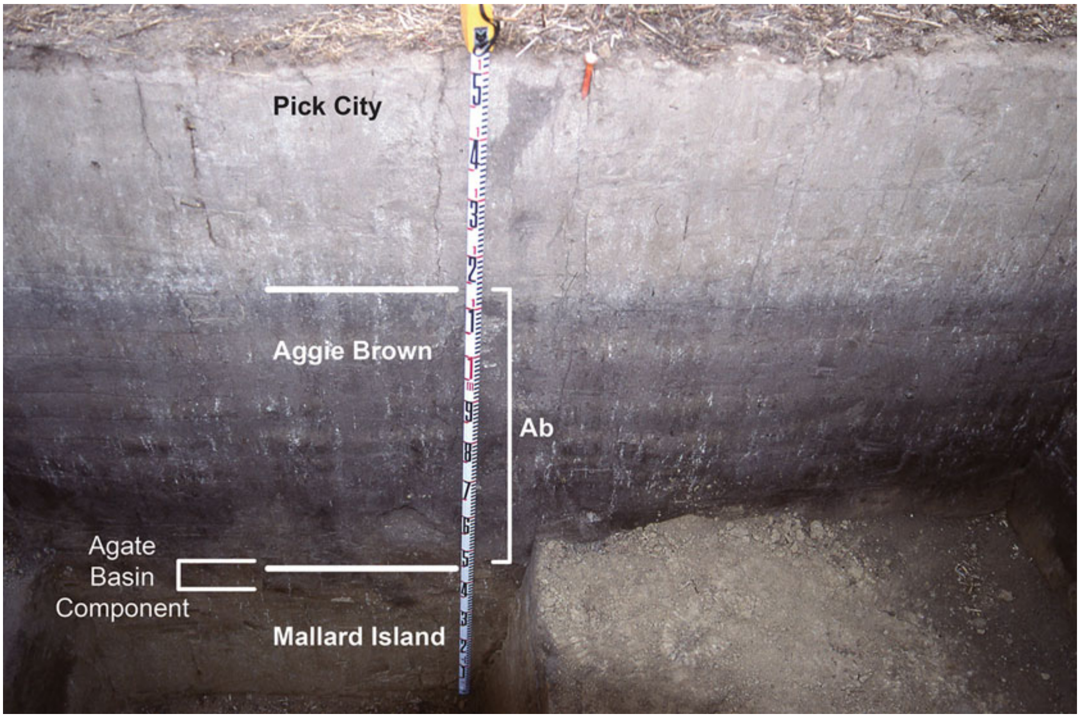
A particularly important characteristic that can be crucial in identifying a buried soil is predictable, lateral variability in morphology ("constancy of relationships" of Brewer, 1972, 333) due to topographic variability (i.e., it is part of a *paleocatena*) and due to parent material variability, both discussed above. The topographic and catenary variability of soils is a unique characteristic particularly important in the identification of buried soils; one not likely mimicked by other geological phenomena (Brewer, 1972; Valentine and Dalrymple, 1975, 1976; Finkl, 1980; Catt, 1986, 168–169). This characteristic of soils allows them to be traced in three dimensions over varying paleotopography. Individual layers of sediment, in contrast, will be confined to particular depositional environments and will thin to nothing as one moves away from that environment (Mandel and Bettis, 2001, 180).

Burial processes

The recognition and interpretation of buried soils can be complicated by several processes that take place before, during, or after burial. As a landscape is buried, some or all of the following processes can operate, depending on landscape position and the nature of the burial process(es).

1. Rapid burial that leaves a complete soil profile preserved under younger sediment. Processes of rapid sedimentation alternating with periods of relative landscape stability and weathering produce multistory sequences of buried soils (Figures 1a, 3, and 5).
2. Erosion prior to burial resulting in a truncated soil profile preserved under younger sediments.
3. Slow burial that allows pedogenesis to keep pace with sedimentation. The result is *upbuilding* (Johnson and Watson-Stegner, 1987) or *overthickening* or *cumulization* of a soil (Buol et al., 1997, 91). Overthickening means that a particular horizon literally becomes thicker than average (relative to more typical horizons associated with similar soils in similar settings in the region) (Figure 6). Overthickened soils are referred to as *accretionary* (Catt, 1990, 6) or *cumulative* (Nikiforoff, 1949, 227–228; Birkeland, 1999, 165–167), and overthickened horizons are called *cumulic* in *Soil Taxonomy* (Soil Survey Staff, 1999, 155). *Soil Taxonomy* (Soil Survey Staff, 1999, 155) further distinguishes between *cumulic* and *pachic* horizons: cumulic horizons can exhibit evidence for stratification (Figure 7), whereas a pachic horizon is overthickened with no evidence of stratification (Figure 8). In general parlance, however, cumulic is usually applied to both situations.

In describing the processes of overthickening, some investigators distinguish between the effects of slow rates of burial and moderate rates of burial (Follmer, 1982, 120; Cremeens and Hart, 1995, 23–24). The difference between an overthickened soil and several welded soils, therefore, is related to local rates of sedimentation. A set of welded soils and a single overthickened soil could be



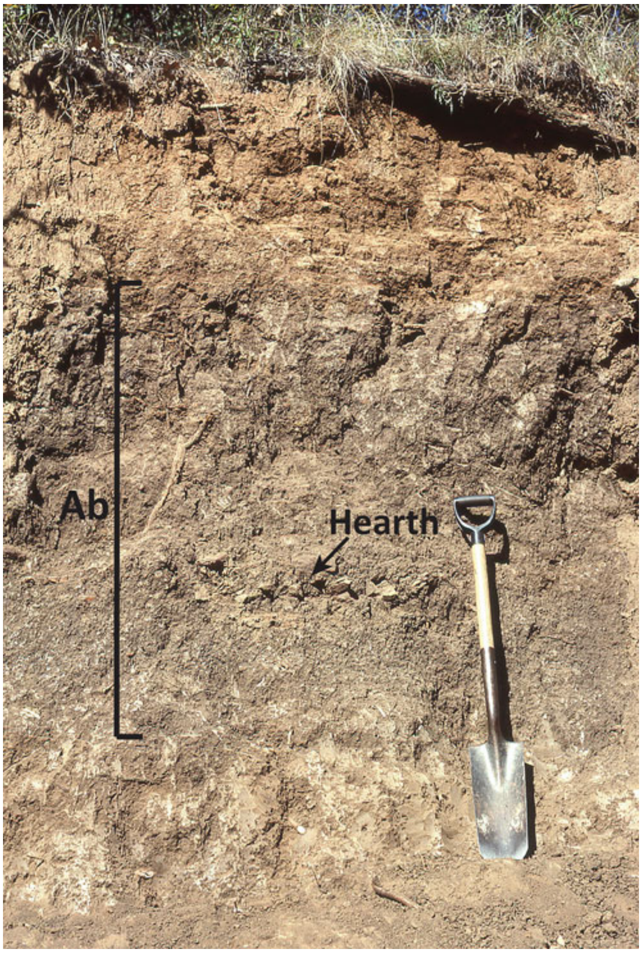
Soil Stratigraphy, Figure 7 The cumulic Ab horizon of a buried paleosol developed in the Aggie Brown Member at the Beacon Island site, an Agate Basin (Paleoindian) bison kill in northwestern North Dakota. The Ab horizon exhibits faint bedding typical of many cumulic soils (Modified from Mandel et al., 2014: Figure 8).

facies of one another (e.g., Kemp et al., 1997). This facies relationship could be at the scale of a floodplain or valley or at a regional scale. Geoarchaeologically, variation in rates of burial of soils and occupation debris will significantly affect where in a soil an archaeological horizon will occur.

Most typically, overthickening affects the A horizon and results from moderate rates of sediment accumulation and burial, where organic matter additions and bioturbation more or less keep pace with sedimentation. Overthickened A horizons are archaeologically significant because they can preserve stratigraphic relationships among artifacts, features, and living surfaces that are otherwise obscured or destroyed in the more typical A horizon. Some accretionary A horizons have weakly expressed stratification, which further aids in archaeological correlation and dating. In some places, the catena variation in soils produces a cumulic A horizon adjacent to an abruptly buried A horizon as in a floodplain abutting a footslope near Cancuen in Guatemala's Peten region (Figure 9).

Pedogenic features are clearly the primary clues to the presence of buried soils, but the morphologic and chemical characteristics typical of soils can undergo moderate to profound changes following burial. Yaalon (1971b) grouped soil horizons and features according to their relative persistence after burial. Generally speaking, the likelihood of preservation or persistence is related to the rate of development of the horizon. Soil features that form rapidly, such as the A horizon, tend to be the least persistent after burial, though many persist for at least 2000 years in the Maya Lowlands (Beach et al., 2015), whereas soil horizons that form more slowly, such as the Bt horizon, tend to be more persistent in buried soils.

The process of soil burial and then post-burial alterations can effectively obscure a buried soil. To summarize, the following questions can be posed as a means of identifying the partial or modified remains of a buried soil (modified from Catt, 1990, 6–7):



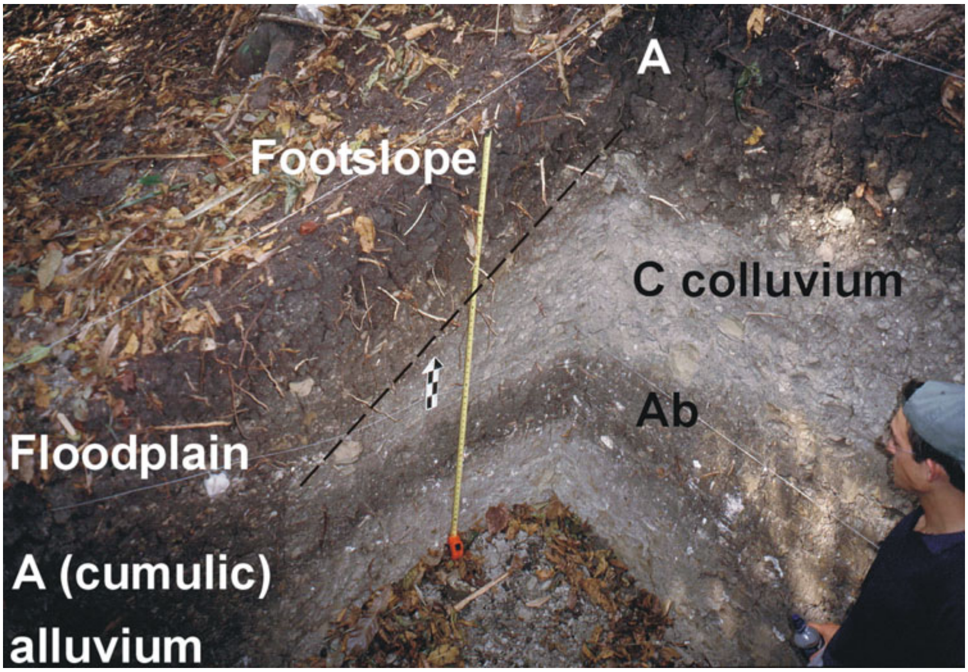
Soil Stratigraphy, Figure 8 A buried soil with a pachic Ab horizon developed in late Holocene alluvium in Fish Creek valley, north-central Texas (Mandel, 1992a). There is no evidence of stratification in the overthickened Ab horizon (Photo by Rolfe D. Mandel).

1. Do the layers concerned contain fossil remains of plants (e.g., roots, charcoal), or artifacts, or geochemical evidence (Beach et al., 2008) indicating the former presence of a land surface?
2. Do the layers display a vertical sequence of horizons that partly or wholly resembles what is typical of known types of modern surface soils?
3. If they are traced laterally, do the layers transgress bedding planes or other rock structures? If so, they are likely to be soil horizons, though in some soils, horizons develop parallel to bedding planes.
4. If they are traced laterally, do the transgressive layers change in character, not only in relation to changes in the underlying sediments or rock type but also in response to changes in the slope of the associated buried land surface? That is, do they form a paleocatena?

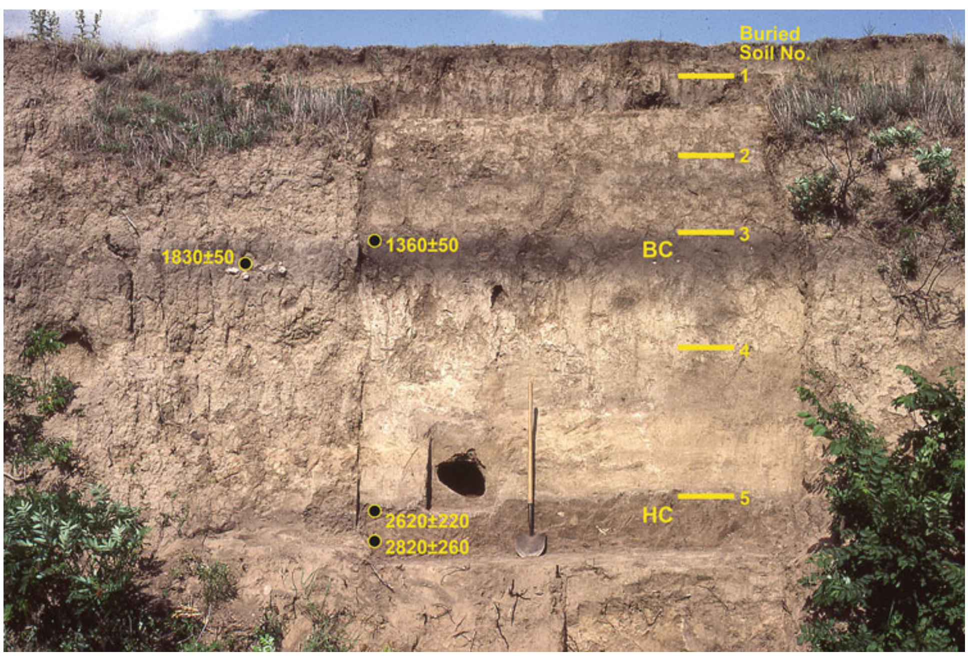
Applications of soil stratigraphy

Recognition of soil stratigraphy has many applications in archaeological investigations. At regional scales, buried soils can be used for stratigraphic correlation of occupation zones and archaeological sites. More locally, in archaeological surveys, buried soils may serve as stratigraphic "markers" used to target particular landform sediment assemblages for deep testing. Buried soils also may be used to determine the boundaries of a site, and where time-diagnostic artifacts and radiocarbon-datable materials are absent, they may be used to estimate the age of cultural deposits. At some archaeological sites, soil stratigraphy is crucial to understanding landscape evolution and site formation processes. A few examples of the application of soil stratigraphy in archaeological investigations are presented below.

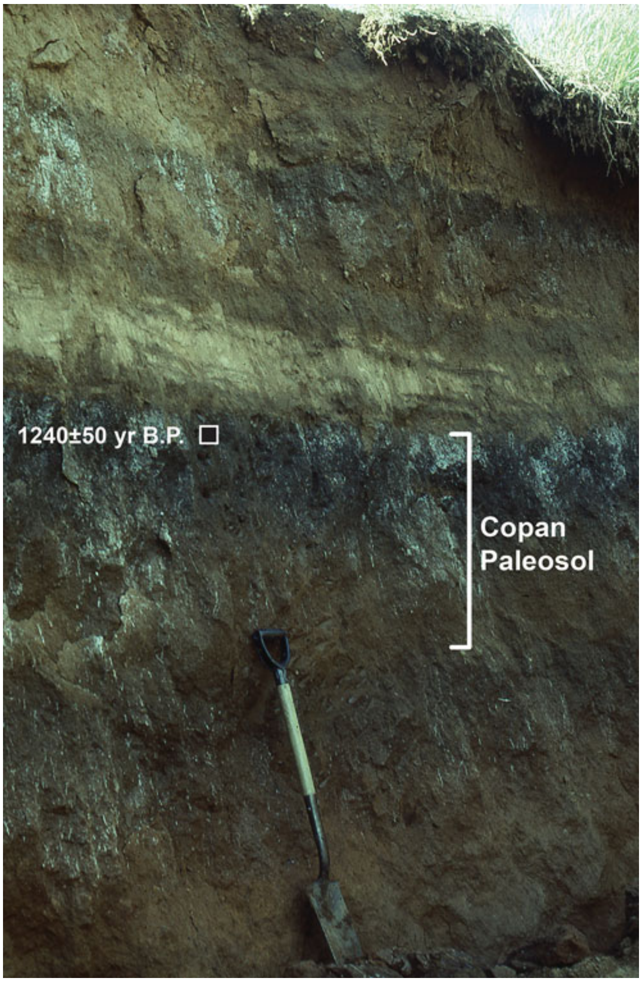
An archaeological survey of the Pawnee River watershed in southwestern Kansas was preceded by an intensive, basin-wide study of alluvium and buried soils to determine their potential for buried cultural deposits. In the valleys of small streams (<5th order), the Hackberry Creek Paleosol and the Buckner Creek Paleosol were identified beneath the lowest terrace (T-1) (Figure 10) (Mandel, 1988; Mandel, 1992b; Mandel, 1994). Radiocarbon ages indicate that the Hackberry Creek Paleosol formed ca. 2800 to 2000 years BP, and the Buckner Creek Paleosol developed around ca. 1700 to 1000 years BP. These two buried soils have thick, moderately expressed Ak-Bk profiles and occur in the valleys of all small streams in the Pawnee River basin. Other buried soils in the late Holocene alluvium comprising the T-1 fill have thin, weakly expressed A-C profiles reflecting only tens of years of pedogenesis (Mandel, 1992b). Stratified late Archaic and Plains Woodland cultural deposits were recorded in the Hackberry Creek and Buckner Creek paleosols, respectively, whereas buried soils with A-C profiles were consistently sterile of archaeological materials (Mandel, 1988; Mandel, 1992b; Mandel, 1994). This finding underscores the axiom that the longer the period over which a soil has developed, the higher its potential for containing cultural deposits at any given location. The Hackberry Creek and Buckner Creek paleosols were targeted for exploration during the subsequent archaeological survey of the Pawnee River basin (Timberlake, 1988).



Soil Stratigraphy, Figure 9 A cumulic soil developed in floodplain alluvium (*left*) is laterally inset against colluvium on a footslope. The buried soil developed in the colluvium dates to ca. 1200 BP (Beach et al., 2006).



Soil Stratigraphy, Figure 10 Soil stratigraphy of the T-1 alluvial fill exposed in the east bank of Buckner Creek at the Buckner Creek site (14HO306) in southwestern Kansas. There are five buried soils, but only two – the Buckner Creek (*BC*) and Hackberry Creek (*HC*) paleosols – can be traced throughout Buckner Creek basin and other drainage systems in the region. The radiocarbon ages were determined on charcoal from cultural features (Modified from Mandel (1992b: Figure 2–13)).



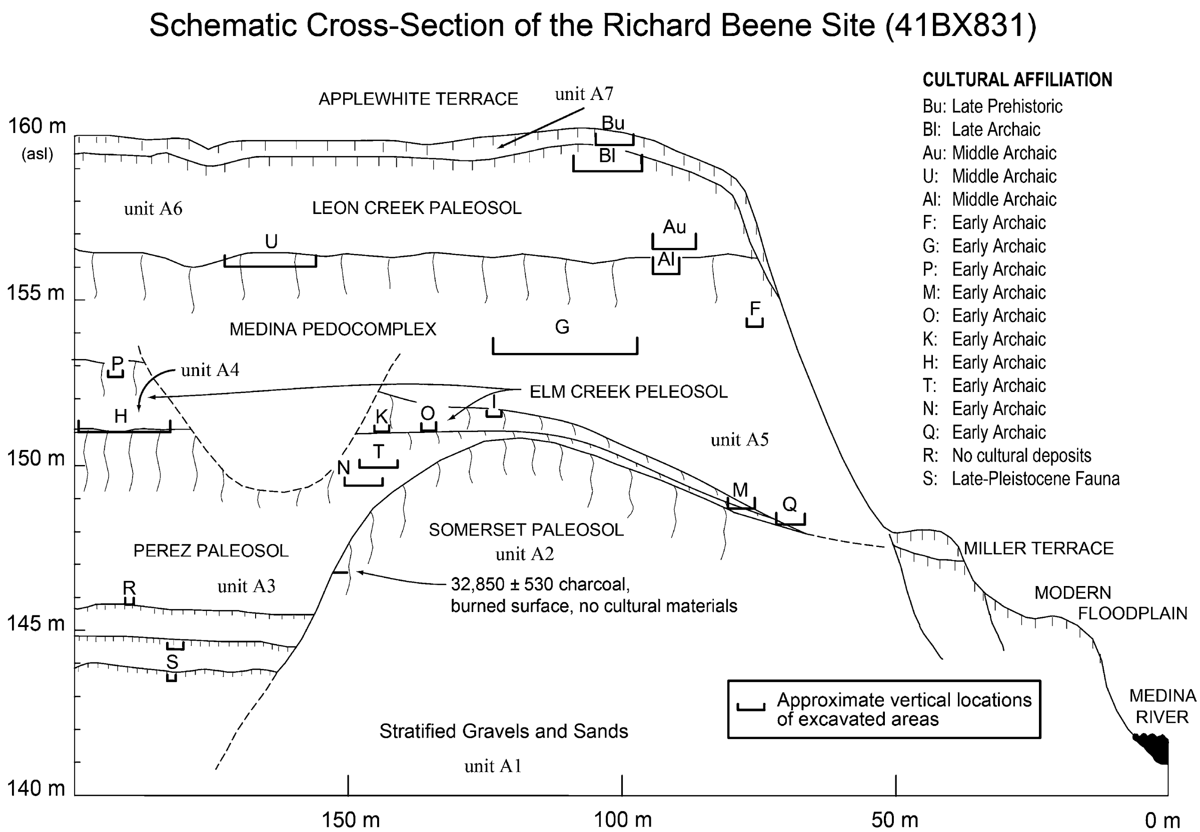
Soil Stratigraphy, Figure 11 The Copan paleosol developed in the T-1 alluvial fill of Elm Creek in Barber County, south-central Kansas. The dark, organic-rich cumulic Ab horizon is 50 cm thick. The radiocarbon age was determined on soil organic matter (Photo by Rolfe D. Mandel).

In situations where time-diagnostic artifacts and radiocarbon-datable materials are absent at a site, buried soils may be used as time-stratigraphic markers to estimate the age of cultural deposits. For example, in eastern Oklahoma and southeastern and south-central Kansas, a buried soil with a distinct overthickened (cumulic) A horizon is developed in late Holocene alluvium (Figure 11). This soil, which is often referred to as the Copan paleosol (Hall, 1977; Artz and Reid, 1984; Artz, 1985; Ferring, 1986; Mandel, 1993a; Mandel, 1993b) or Caddo paleosol (Hall, 1980; Ferring, 1982; Lintz and Hall, 1983), developed between ca. 2000 and 1000 years ago. Because the buried soil is well dated and easy to recognize in late Holocene alluvial sections, it is a time-stratigraphic marker and has been used to estimate the age of cultural deposits contained in its horizons (e.g., Mandel, 2013b).

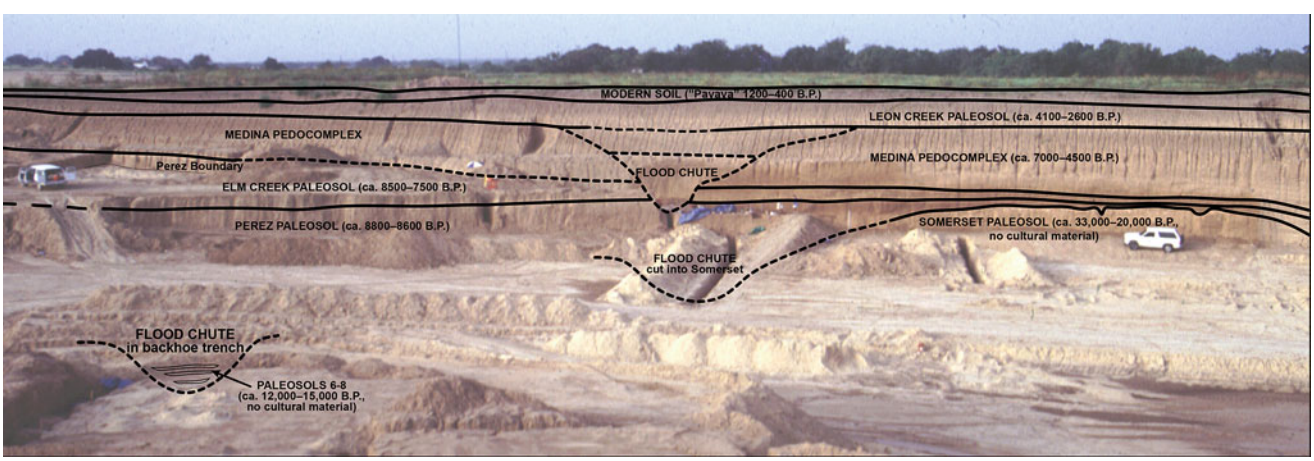
The boundaries of deeply buried archaeological sites may be difficult to determine by traditional excavation methods for logistical reasons. However, if the buried materials are on former stable surfaces (i.e., associated with distinct buried soils), soil stratigraphy, combined with deep testing, may be used to determine the spatial limits of cultural deposits. For example, investigation of deeply buried cultural deposits in alluvium at the Richard Beene site (41BX831) in the Medina River valley of south-central Texas identified seven major depositional units beneath the Applewhite terrace (Figure 12) (Mandel et al., 2007). Soils are developed at the top of each unit, and archaeological materials are on and within the buried soils. The thickness of the fill terrace (>20 m), combined with complex stratigraphy that is a product of alluvial cutting and filling, presented a challenge to document the lateral extent of the cultural deposits. Mandel et al. (2007) defined the spatial limits of each buried cultural zone by using cores and a long, deep trench to trace the artifact-bearing buried soils, all designated as paleosols, and to identify their stratigraphic complexities (Figure 13). These findings were critical to the development of excavation strategies that targeted some areas of the site for investigation while avoiding other areas (Thoms, 2007).

In the Maya Lowlands, soil catena excavations at Blue Creek, Belize, uncovered a series of paleosols lumped together at the Eklu'um paleosol buried by colluvial, alluvial, hydrogeological, and anthropogenic processes from 2000 to 1000 years ago (Beach et al., 2008) (Figure 14). The general driver was human slope alteration creating erosion along the slope but with aggradation in adjacent karst sinks, alluvial fans, footslopes, and the Rio Bravo floodplain. In the floodplain and some karst sinks, aggradation occurred by water table rise with gypsum precipitation and Maya adaptation with canalization and field raising, both obliterating and burying Vertisol, Mollisol, and Histosol paleosols.

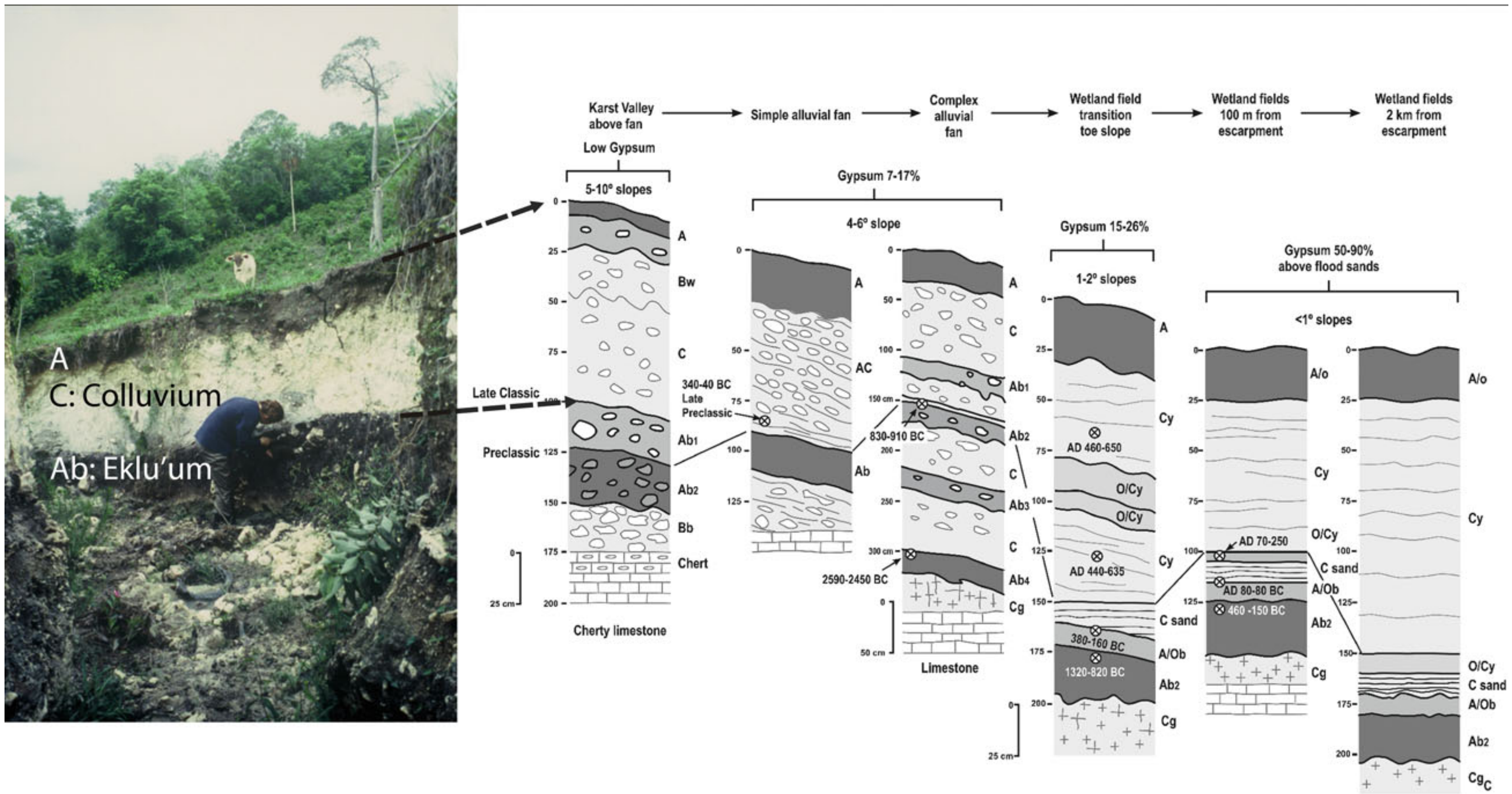
Soil stratigraphy has long been applied for correlation of geologic deposits in Europe and Asia. This work also has been carried over into geoarchaeological correlations. In Tajikistan, buried soils in the loess record combined with paleomagnetic data have been used to correlate the Paleolithic archaeology and to provide age estimates for occupation zones at specific sites (see "Loessic Paleolithic, Tajikistan" entry in this volume). More locally, soils in the alluvial stratigraphic record of



Soil Stratigraphy, Figure 12 Schematic cross-section of the south wall of the 20-m-deep spillway trench at the Richard Beene site showing stratigraphic units, soils, excavated areas, and archaeological stratigraphy (Modified from Mandel et al. (2007: Figure 3.3)).



Soil Stratigraphy, Figure 13 The central section of the south wall of the 20-m-deep spillway trench at the Richard Beene site showing the paleosols and associated radiocarbon ages determined on charcoal (Modified from Thoms (2007: Figure 4.6)).



Soil Stratigraphy, Figure 14 A catena near Blue Creek, Belize, showing the Preclassic Eklu'um paleosol predating 2000 BP buried by colluvium and alluvium with secondary accumulation of gypsum (Beach et al., 2008).

terraces of the Don River in southwestern Russia have been similarly applied to correlate and date the several dozen late Middle and Upper Paleolithic sites in the Kostenki-Borschevo area (see "Kostenki, Russia" entry in this volume).

Bibliography

Artz, J. A., 1985. A soil-geomorphic approach to locating buried Late-Archaic sites in northeast Oklahoma. *American Archaeology*, **5**, 142–150.

Artz, J. A., and Reid, K. C., 1984. Geoarchaeological investigations in Cotton Creek valley. In Reid, K. C., and Artz, J. A. (eds.), *Hunters of the Forest Edge: Culture, Time, and Process in the Little Caney Basin*. Tulsa, OK: University of Tulsa, Laboratory of Archaeology. Contributions in Archaeology 14, pp. 97–186.

Beach, T., Dunning, N., Luzzadder-Beach, S., Cook, D. E., and Lohse, J., 2006. Ancient Maya impacts on soils and soil erosion in the central Maya Lowlands. *Catena*, **65**(2), 166–178.

Beach, T., Luzzadder-Beach, S., Dunning, N., and Cook, D., 2008. Human and natural impacts on fluvial and karst depressions of the Maya Lowlands. *Geomorphology*, **101**(1–2), 308–331.

Beach, T., Luzzadder-Beach, S., Cook, D., Dunning, N., Kennett, D. J., Krause, S., Terry, R., Trein, D., and Valdez, F., 2015. Ancient Maya impacts on the earth's surface: an early anthropocene analog? *Quaternary Science Reviews*, **124**, 1–30.

Bettis, E. A., III, 1992. Soil morphologic properties and weathering zone characteristics as age indicators in Holocene alluvium in the Upper Midwest. In Holliday, V. T. (ed.), *Soils in Archaeology: Landscape Evolution and Human Occupation*. Washington, DC: Smithsonian Institution Press, pp. 119–144.

Birkeland, P. W., 1999. *Soils and Geomorphology*, 3rd edn. New York: Oxford University Press.

Bos, R. H. G., and Sevink, J., 1975. Introduction of gradational and pedomorphic features in descriptions of soils: a discussion of the soil horizon concept with special reference to paleosols. *Journal of Soil Science*, **26**(3), 223–233.

Brewer, R., 1972. Use of macro- and micromorphological data in soil stratigraphy to elucidate surficial geology and soil genesis. *Journal of the Geological Society of Australia*, **19**(3), 331–344.

Brewer, R., Crook, K. A. W., and Speight, J. G., 1970. Proposal for soil stratigraphic units in the Australian stratigraphic code. Report by the subcommittee for soil-stratigraphic nomenclature. *Journal of the Geological Society of Australia*, **17**(1), 103–111.

Buol, S. W., Hole, F. D., McCracken, R. J., and Southard, R. J., 1997. *Soil Genesis and Classification*, 4th edn. Ames, IA: Iowa State University Press.

Butler, B. E., 1959. *Periodic Phenomena in Landscapes as a Basis for Soil Studies*. Melbourne, Australia: Commonwealth Scientific and Industrial Research Organization. CSIRO Soil Publication 14.

Catt, J. A., 1986. *Soils and Quaternary Geology: A Handbook for Field Scientists*. Oxford: Clarendon.

Catt, J. A., 1990. Paleopedology manual. *Quaternary International*, **6**, 1–95.

Catt, J. A., 1998. Report from working group on definitions used in paleopedology. *Quaternary International*, **51–52**, 84.

Cremeens, D. L., and Hart, J. P., 1995. On chronostratigraphy, pedostratigraphy, and archaeological context. In Collins, M. E., Carter, B. J., Gladfelter, B. G., and Southard, R. J. (eds.), *Pedological Perspectives in Archaeological Research*. Madison: Soil Science Society of America. SSSA Special Publication, 44, pp. 15–33.

Crook, K. A. W., and Coventry, R. J., 1967. Climatically controlled Quaternary sedimentation and soils in Ryans Creek Valley, N.S.W. In *Congress of the Australian and New Zealand Association for the Advancement of Science, Section C, Abstracts* T9-11.

Duchaufour, P., 1982. *Pedology, Pedogenesis, and Classification*, translated by T. R. Paton. Boston: Allen and Unwin.

Fenwick, I. M., 1985. Paleosols: problems of recognition and interpretation. In Boardman, J. (ed.), *Soils and Quaternary Landscape Evolution*. Chichester, UK: Wiley, pp. 3–21.

Ferring, C. R. (ed.), 1982. *The Late Holocene Prehistory of Delaware Canyon, Oklahoma*. Denton: Institute of Applied Sciences, North Texas State University. Contributions in Archaeology 1.

Ferring, C. R., 1986. Rate of fluvial sedimentation: implications for archaeological variability. *Geoarchaeology*, **1**(3), 259–274.

Finkl, C. W., Jr., 1980. Stratigraphic principles and practices as related to soil mantles. *Catena*, **7**(2–3), 169–194.

Follmer, L. R., 1982. The geomorphology of the Sangamon surfaces: its spatial and temporal attributes. In Thorn, C. E. (ed.), *Space and Time in Geomorphology*. London: Allen and Unwin. Binghamton Symposia in Geomorphology 12, pp. 117–146.

Hall, S. A., 1977. Geology and palynology of archaeological sites and associated sediments. In Henry, D. O. (ed.), *The Prehistory of the Little Caney River, 1976 Season*. Tulsa: University of Tulsa, Laboratory of Archaeology. Contributions in Archaeology 1, pp. 13–41.

Hall, S. A., 1980. Paleoenvironmental synthesis of Hominy Creek valley: pollen and land snail evidence. In Henry, D. O. (ed.), *The Prehistory and Paleoenvironment of Hominy Creek Valley, 1978 Field Season*. Tulsa: University of Tulsa, Laboratory of Archaeology. Contributions in Archaeology 6, pp. 44–55.

Holliday, V. T., 2004. *Soils in Archaeological Research*. New York: Oxford University Press.

Ito, T., Shoji, S., Shirato, Y., and Ono, E., 1991. Differentiation of a spodic horizon from a buried a horizon. *Soil Science Society of America Journal*, **55**(2), 438–442.

Jenkins, D., 1985. Chemical and mineralogical composition in the identification of paleosols. In Boardman, J. (ed.), *Soils and Quaternary Landscape Evolution*. Chichester, UK: Wiley, pp. 23–43.

Johnson, D. L., and Watson-Stegner, D., 1987. Evolution model of pedogenesis. *Soil Science*, **143**(5), 349–366.

Kemp, R. A., Derbyshire, E., and Meng, X.-M., 1997. Micromorphological variation of the S1 paleosol across northwest China. *Catena*, **31**(1–2), 77–90.

Kraus, M. J., 1999. Paleosols in clastic sedimentary rocks: their geologic applications. *Earth-Science Reviews*, **47**(1–2), 41–70.

Kraus, M. J., and Aslan, A., 1999. Palaeosol sequences in floodplain environments: a hierarchical approach. In Thiry, M., and Simon-Coinçon, R. (eds.), *Palaeoweathering, Palaeosurfaces and Related Continental Deposits*. Oxford: Blackwell. International Association of Sedimentologists, Special Publication, 27, pp. 303–321.

Kraus, M. J., and Brown, T. M., 1988. Pedofacies analysis; a new approach to reconstructing ancient fluvial sequences. In Reinhardt, J., and Sigleo, W. R. (eds.), *Paleosols and Weathering Through Geologic Time: Principles and Applications*. Boulder, CO: Geological Society of America. GSA Special Paper 216, pp. 143–152.

Lintz, C., and Hall, S. P., 1983. *The Geomorphology and Archaeology of Carnegie Canyon, Fort Cobb Laterals Watershed, Caddo County, Oklahoma*. Oklahoma City: Oklahoma Conservation Commission.

Mandel, R. D., 1988. Geomorphology of the Pawnee River valley. In Timberlake, R. D. (ed.), *Phase II Archaeological and Geomorphological Survey of the Proposed Pawnee River Watershed, Covering Subwatersheds 3 through 7, Ness, Fort, Lane, and Finney Counties, Southwest Kansas*. Topeka: Kansas Historical Society, pp. 68–115.

Mandel, R. D., 1992a. Geomorphology of the upper Brazos River Valley, North-Central Texas. In Saunders, J. W., Mueller-Wille, C. S., and Carlson, D. L. (eds.), *An Archeological Survey of the Proposed South Bend Reservoir Area, Young, Stevens, and Throckmorton Counties, Texas*. College Station, TX: Archaeological Research Laboratory, Texas A&M University. Archeological Surveys 6, pp. 53–84.

Mandel, R. D., 1992b. Soils and Holocene landscape evolution in central and southwestern Kansas: implications for archaeological research. In Holliday, V. T. (ed.), *Soils in Archaeology: Landscape Evolution and Human Occupation*. Washington, DC: Smithsonian Institution Press, pp. 41–117.

Mandel, R. D., 1993a. Geomorphology. In Weston, T. (ed.), *Phase II Cultural Resource Survey of High Potential Areas within the Southeast Kansas Highway Corridor*. Topeka: Kansas State Historical Society. Contract Archeology Publication 10, pp. 44–121.

Mandel, R. D., 1993b. Geomorphology. In Hawley, M. F. (ed.), *Cultural Resource Investigations for the U.S. Highway 166 Corridor*. Topeka: Kansas State Historical Society. Contract Archeology Publication 11, pp. 24–75.

Mandel, R. D., 1994. *Holocene Landscape Evolution in the Pawnee River Valley, Southwestern Kansas*. Lawrence/Topeka: Kansas Geological Survey/Kansas State Historical Society. Kansas Geological Survey Bulletin 236.

Mandel, R. D., 2013a. Geomorphological investigation. In Palmer, L., Buhta, A. A., Kruse, J. M., and Mandel, R. D. (eds.), *An Archeological and Geomorphological Survey of Select Lands Along Oak Creek and Salt Creek in the Vicinity of Lincoln, Lancaster County, Nebraska*. Sioux Falls, SD: Archeology Laboratory, Augustana College. Archeological Contract Series 260, pp. 90–128.

Mandel, R. D., 2013b. Geoarchaeology and paleoenvironmental context of the Eastep Site (14MY388), southeast Kansas. *The Kansas Anthropologist*, **33**, 159–174.

Mandel, R. D., and Bettis, E. A., III, 2001. Use and analysis of soils by archaeologists and geoscientists: a North American perspective. In Goldberg, P., Holliday, V. T., and Ferring, C. R. (eds.), *Earth Sciences and Archaeology*. New York: Kluwer Academic/Plenum Publishers, pp. 173–204.

Mandel, R. D., Jacob, J. S., and Nordt, L. C., 2007. Geoarchaeology of the Richard Beene site. In Thoms, A. V., and Mandel, R. D. (eds.), *Archaeological and Paleoecological Investigations at the Richard Beene Site (41BX831), South Central Texas*. College Station: Texas A&M University. Center for Ecological Archaeology, Reports of Investigations no 8, pp. 27–60.

Mandel, R. D., Murphy, L. R., and Mitchell, M. D., 2014. Geoarchaeology and paleoenvironmental context of the Beacon Island site, an Agate Basin (Paleoindian) bison kill in northwestern North Dakota, USA. *Quaternary International*, **342**, 91–113.

Morrison, R. B., 1967. Principles of quaternary soil stratigraphy. In Morrison, R. B., and Wright, H. E., Jr. (eds.), *Quaternary Soils*. Reno, NV: University of Nevada, Desert Research Institute, Center for Water Resources Research, pp. 1–69.

Morrison, R. B., 1978. Quaternary soil stratigraphy – concepts, methods, and problems. In Mahaney, W. C. (ed.), *Quaternary Soils*. Norwich, UK: Geo Abstracts, pp. 77–108.

NACSN (North American Commission on Stratigraphic Nomenclature), 2005. North American stratigraphic code. *American Association of Petroleum Geologists Bulletin*, **89**(11), 1547–1591.

Nikiforoff, C. C., 1949. Weathering and soil evolution. *Soil Science*, **67**(3), 219–230.

Pyddoke, E., 1961. *Stratification for the Archaeologist*. London: Phoenix House.

Ruhe, R. V., and Olson, C. G., 1980. Soil welding. *Soil Science*, **130**(3), 132–139.

Rutter, N. W., 1978. Soils in archaeology. In Rutherford, G. K., Savage, P. J., and Warkentin, B. P. (eds.), *The Geosciences in Canada, 1977: Annual Report and Review of Soil Science*. Ottawa: Geological Survey of Canada. Geological Survey of Canada Paper 78–6.

Soil Survey Staff, 1999. *Soil Taxonomy: A Basic System of Soil Classification for Making and Interpreting Soil Surveys*, 2nd edn. Washington, DC: US Department of Agriculture, Natural Resources Conservation Service. USDA Agriculture Handbook 436.

Tamplin, M. J., 1969. The application of pedology to archaeological research. In Pawluk, S. (ed.), *Pedology and Quaternary Research*. Edmonton: The University of Alberta Printing Department, pp. 153–161.

Tandon, S. K., and Kumar, S., 1999. Semi-arid/arid zone calcretes: a review. In Singhvi, A. K., and Derbyshire, E. (eds.), *Paleoenvironmental Reconstruction in Arid Lands*. Rotterdam: A.A. Balkema, pp. 109–152.

Thoms, A. V., 2007. Excavation areas and site-formation contexts. In Thoms, A. V., and Mandel, R. D. (eds.), *Archaeological and Paleoecological Investigations at the Richard Beene Site (41BX831), South Central Texas*. College Station: Texas A&M University. Center for Ecological Archaeology, Reports of Investigations No 8, pp. 61–86.

Thorson, R. M., 1990. Geologic contexts of archaeological sites in Beringia. In Lasca, N. P., and Donahue, J. (eds.), *Archaeological Geology of North America*. Boulder, CO: Geological Society of America. Centennial Special, Vol. 4, pp. 399–420.

Timberlake, R. D. (ed.), 1988. *Phase II Archaeological and Geomorphological Survey of the Proposed Pawnee River Watershed, Covering Subwatersheds 3 through 7, Ness, Fort, Lane, and Finney Counties, Southwest Kansas*. Topeka, KS: Kansas Historical Society.

Valentine, K. W. G., and Dalrymple, J. B., 1975. The identification, lateral variation and chronology of two buried paleocatenas at Woodhall Spa and West Runton, England. *Quaternary Research*, **4**, 551–590.

Valentine, K. W. G., and Dalrymple, J. B., 1976. Quaternary buried paleosols: a critical review. *Quaternary Research*, **6**(2), 209–222.

Van Dijk, D. C., Riddler, A. M. H., and Rowe, R. K., 1968. Criteria and problems in groundsurface correlations with reference to a regional correlation in south-eastern Australia. In *Transactions of the 9th International Congress of Soil Science, Adelaide*. Sydney: International Society of Soil Science and Angus & Robertson, Vol. 4, pp. 131–138.

Waters, M. R., 1992. *Principles of Geoarchaeology: A North American Perspective*. Tucson, AZ: The University of Arizona Press.

Yaalon, D. H., 1971a. Criteria for the recognition and classification of paleosols. In Yaalon, D. H. (ed.), *Paleopedology: Origin, Nature and Dating of Paleosols*. Jerusalem: International Society of Soil Science and Israel Universities Press, pp. 153–158.

Yaalon, D. H., 1971b. Soil-forming processes in time and space. In Yaalon, D. H. (ed.), *Paleopedology: Origin, Nature and Dating of Paleosols*. Jerusalem: International Society of Soil Science and Israel Universities Press, pp. 29–39.

Cross-references

Kostenki, Russia
Loessic Paleolithic, Tajikistan
Site Formation Processes
Soil Geomorphology
Soil Survey
Soils
Stratigraphy

SOIL SURVEY

Vance T. Holliday[1] and Rolfe D. Mandel[2]
[1]Anthropology and Departments Geosciences, University of Arizona, Tucson, AZ, USA
[2]Department of Anthropology, University of Kansas, Lawrence, KS, USA

Introduction

Soil survey and mapping is one of the most fundamental and best-known activities in pedology. The production of soil maps based on systematic soil surveys was one of the primary driving forces in pedologic research in both academic and governmental settings in the USA and worldwide through much of the twentieth century (Simonson, 1987, 1997; Yaalon and Berkowicz, 1997). Soil maps have been prepared for a variety of uses at scales ranging from a few hectares to continental and global. Published soil surveys contain a wealth of data on landscapes as well as soils, but they are generally an underutilized (and likely a misunderstood) resource in geoarchaeology, probably because of their agricultural and land-use orientation.

Many countries in the world have national soil surveys whose primary mission is mapping and inventorying the nation's soil resources. In the USA, soil survey is a cooperative venture of federal agencies, state agencies, including the Agricultural Experiment Stations, and local agencies, coordinated by the National Cooperative Soil Survey (Soil Survey Division Staff, 1993, 11). The principal federal agency involved in soil survey is the National Resource Conservation Service (NRCS) (formerly the Soil Conservation Service, SCS) of the US Department of Agriculture (USDA). Published county soil surveys are their most widely known and widely used product. These surveys contain information regarding soils and land-use capability, and many include descriptions of soil properties of interest to engineers. The surveys also are a remarkable source of maps and air photographs. Most archaeologists are aware of this resource, but its usefulness sometimes seems to be overestimated or misunderstood in some cases or underused in others (Voight and O'Brien, 1981), as illustrated below. The county soil surveys have potential for archaeological applications, but their purpose and limitations must be recognized.

The USDA county soil surveys and those of most nations are prepared for land-use planning, especially for soil conservation programs, planning agriculture programs, financial credit, zoning, construction and engineering purposes, and land evaluation (Butler, 1980, 1–7; King, 1983, 102–103; Broderson, 1994; Buol et al., 2011, 32–34). The photomaps in the soil surveys are produced at a variety of scales, ranging from 1:7,920 to 1:31,680, and at various levels of detail (Soil Survey Division Staff, 1993, 47–46). Most of the photomaps, however, are at a scale of 1:20,000. The NRCS digitized these maps so they can be electronically accessed. More generalized soil maps of individual states in the USA typically are in the range of 1:250,000–1:2,000,000. In contrast, King (1983) describes soil maps for a part of Cyprus produced at two scales: 1:25,000 and 1:200,000. Globally, FAO (2006) produced a 10-volume set of soil maps of the world at 1:500,000.

Limitations of soil surveys

The purpose and preparation of soil surveys impose a number of limits on their utility in archaeological research. One limit on their use for site-specific interpretations is the generalization inherent in defining mapping units. Soil variability and how to deal with it in mapping is a significant issue in the pedologic literature (e.g., Wilding and Drees, 1983; Mausbach and Wilding, 1991). The distribution of soils across a landscape may be too complex to map accurately either due to complexities in their evolution (i.e., variability in the factors or processes of soil formation) or due to variability in their taxonomic classification (see entry on Soils in this volume).

> Because limitations imposed by scale and legibility do not permit exact representation of all detail observed (or inferred) in the field, *mapping units cannot correspond exactly to the taxonomic or genetic units that they represent*. . .. Mapping units therefore typically include areas of soils other than those specified in the legend. . .. An important practical problem in most national soil surveys is that *the map user has no way to learn of the amount, character, and pattern of these variations, because he or she must rely completely upon the map, its legend, and the accompanying report, which usually presents little detail on such matters*" (emphasis added). (Hole and Campbell, 1985, 113)

For example, the minimum size area permitted for delineation on most county soil surveys is 1 ha. Depending on the scale of the map, the maximum size permitted may be as large as 4 ha (Soil Survey Division Staff, 1993, 52–55, Table 2.1). Therefore, the scale of many archaeological sites is smaller than most soil mapping units and the variability inherent in those mapping units. The problem of scale in dealing with soil mapping units and archaeological sites has been confronted in archaeological surveys around the world (e.g., King, 1983; Jones, 1990).

The boundaries of a particular mapping unit do not always represent actual soil boundaries because soils may grade from one type into another rather than having sharp contacts like many geologic units. Soil boundaries are rarely as distinct as the map lines used to symbolize them (Hole and Campbell, 1985, 101). The fundamental issue of scale in soil mapping is that the soils that can be seen at an archaeological site may not necessarily be those indicated on the published soil survey of the area.

The focus on the *soil series* further inhibits the geoarchaeological applications of county soil surveys. The soil series is the fundamental mapping unit in county soil surveys. Soil series are defined on the basis of one or more of the following characteristics: kind, thickness, and arrangement of soil horizons along with the color, texture, structure, consistence, pH, content of carbonates and other salts, content of coarse fragments, and mineralogy. A *soil association* is a more generalized mapping unit (e.g., used on county-scale or state-wide soil maps), typically based on two or more similar series plus inclusions. The soil series is the most homogeneous grouping of soils made in Soil Taxonomy (Buol et al., 2011, 33, 212–214). Soil series are defined strictly as subdivisions within the classificatory system (see Soils entry) and are intended to "record pragmatic distinctions, i.e., to be keyed to soil usefulness" (Simonson, 1997, 80). The emphasis on specific physical or chemical characteristics to define soil series results in mapping units that are rarely related to one another except taxonomically. For example, "the soil classification relates an Aquept [an Inceptisol] in a certain map unit to other Inceptisols throughout the world. But it does not address the relationship between the map unit containing the Aquept and other map units that occur adjacent to it in the survey area" (Swanson, 1990, 52).

The heavy emphasis on the soil series but the lack of information regarding genetic relationships among series tends to promote a view of the soil landscape as if the soil series are independent segments, like tiles in a tile floor. For this reason, as well as others discussed below, the soil series may not be relevant in regional geoarchaeological or soil-geomorphic investigations. Instead, the *great group* or perhaps *subgroup* level of Soil Taxonomy may be more meaningful and informative, though investigators will need to be familiar with series names in order to read soil maps. However, as discussed later, in some cases soil series may be used to map landform sediment assemblages dating to specific periods. Such information is useful for understanding the geomorphic settings of archaeological sites and predicting and assessing temporal and spatial patterns of cultural deposits across a region.

Typically, soil surveys are not designed for use as guides to local geology or geomorphology or to aid in interpreting or reconstructing the past, and few contain substantive data on local soil-forming processes and factors. In the USDA county surveys, genetic and factorial relationships among series as well as geologic and other "physiographic" aspects were expressly de-emphasized, despite work that showed a good relationship (Simonson, 1997; Holliday et al., 2002). The degree to which the USDA county surveys accurately depict soil-geomorphic relations will vary tremendously from survey to survey, depending on the size of the features of interest, the area, and the training and experience of the mappers.

There are several other reasons why the distribution of modern soil series may be poor indicators of site distributions (following Warren et al., 1981):

1. The factors and processes of soil formation can and do change over time, and the more time that passes since occupation of an archaeological site, the more likely that the environment has changed and the more likely that such change was significant in terms of either settlement or soil formation or both.
2. Human perceptions of soil quality or environmental quality change through time, i.e., successive groups of occupants may have different criteria for what constitutes "good" or attractive soils or environments even though there were no substantive changes in these characteristics.
3. Finally, soils are not necessarily the best indicator of past environments (e.g., Voight and O'Brien, 1981).

Archaeological applications of soil surveys

The characteristics of soil surveys described above have resulted in their being minimally used in geoarchaeological research. Nevertheless, they have some utility in addition to providing maps and aerial photos. Specific soil series sometimes are associated with specific landforms, and thus they can provide clues to archaeologically significant settings (Saucier, 1966; Almy, 1978; Litwinionek et al., 2003; Mandel, 2006a; West, 2012). There are several examples in which the distribution of specific soil series was used to predict the presence or absence of sites by simply looking at the correlation between soil series and site frequency (Almy, 1978; Voight and O'Brien, 1981; Warren et al., 1981; Warren and O'Brien, 1981, 1982; Warren, 1982a). Research on soils, geomorphology, and geoarchaeology along the Kansas River (Johnson and Martin, 1987; Sorenson et al., 1987; Johnson and Logan, 1990; Mandel, 1995, 2006b) provide a good illustration of the relationship between traditional soil survey mapping, soil series, and soil-geomorphic relationships along terraces.

More broadly, drainage characteristics of soils, emphasized on soil surveys, can be useful for archaeological site prediction, as better-drained soils are more likely to contain sites (i.e., prehistoric occupants probably preferred better-drained settings for most of their activities) (Saucier, 1966; Plog, 1971; Lovis, 1976; Almy, 1978; O'Brien et al., 1982; Warren, 1982b; Mandel and Bettis, 2001, 182).

The soils themselves have some interpretive value for archaeological research. Assessing relative landscape age based on soil classification is perhaps the most useful yet most underutilized aspect of soil surveys in geoarchaeology and geomorphology. Soil Taxonomy was not designed to be a means of estimating soil age or to make other sorts of genetic interpretations, but with some experience and caution, age assessments can be offered based on horizon characteristics, particularly the B horizon, and based on classification (Artz, 1985; Bettis, 1992; E. A. Bettis, 2001, "personal communication").

A number of studies (e.g., Bettis and Benn, 1984; Artz, 1985; Bettis, 1992; Mandel, 1992, 1994, 2006a; Monger, 1995; Stafford and Creasman, 2002; West, 2012) have considered the relationship between magnitude of soil development and age of geomorphic surfaces to develop archaeological predictive models. These models use soil classification and taxonomy presented in soil surveys to estimate the relative age of surface soils, which in turn provides a minimum age for associated landforms (Holliday, 2004) (see entry on "Geomorphology" in this volume). The estimated ages then can be used to assign an archaeological potential to specific landforms, which are generally described as having low, medium, or high potential (Mandel, 1992, 1994). For example, on the valley floors of streams, strongly developed surface soils with an argillic (Bt) horizon have a higher potential to yield prehistoric cultural deposits than weakly developed soils that lack a B horizon. Such estimated ages can even be used to identify landforms, such as floodplains, natural levees, terraces, and alluvial fans, that have potential for yielding archaeological materials dating to specific cultural periods, such as Paleoindian, Archaic, and Woodland (Artz, 1985; Stafford and Creasman, 2002; Mandel, 2006a, 2006b).

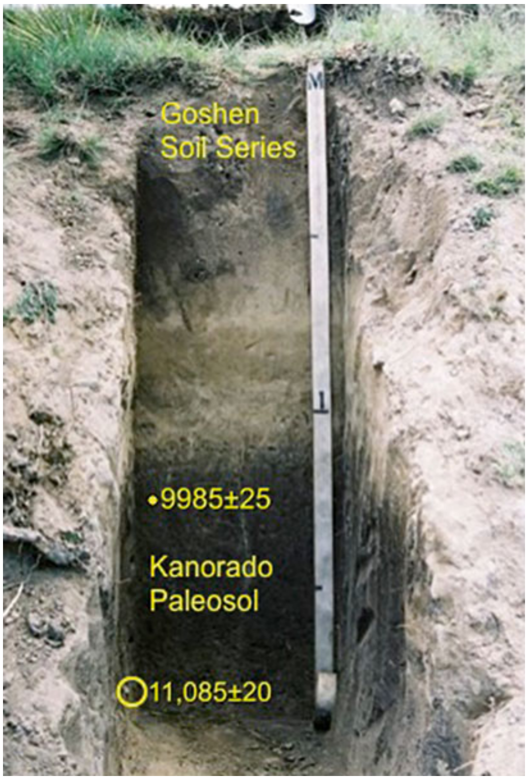
In a study of the central Des Moines River valley, Bettis and Benn (1984) demonstrated that certain properties of surface soils developed in the Holocene alluvium of Midwestern streams are age diagnostic. For example, surface soils formed in early and Middle Holocene alluvium are Mollisols with Bt horizons or Alfisols. In contrast, surface soils developed in late Holocene alluvium are Mollisols or Inceptisols with cambic (Bw) horizons, or Mollisols that lack B horizons. This soil information, much of which was gleaned from soil surveys, was used to construct maps that show the distribution of landform sediment assemblages dating to different periods of the Holocene. In turn, archaeologists used the maps to devise sampling strategies for locating cultural resources in the valley landscape (see entry on "Geomorphology" in this volume). Such soil-based information also can provide archaeologists with estimates of past landscapes removed by fluvial processes (Mandel and Bettis, 2001, 182).

Some soil surveys in the USA were prepared with the type of background information that permits their use as guides to archaeologically significant soil-geomorphic relationships. From the late 1950s into the 1970s, the USDA sponsored a series of research projects focused on understanding soil-geomorphic relations in various environments in the USA. One of these projects focused on late Pleistocene and Holocene landscapes in the Willamette River valley of northwestern Oregon (Balster and Parsons, 1968; Parsons et al., 1970). The model of fluvial landscape evolution that resulted from this work has been used for mapping soils along rivers in the region (e.g., Gerig, 1985) and on the Pacific coast (e.g., Shipman, 1997). These county soil surveys should be useful in predicting the likely presence or absence of archaeological sites, and their age, either buried or at the surface. In south-central New Mexico and far western Texas, soil-geomorphic mapping was carried out to predict archaeological site locations and to interpret archaeological finds in the desert terrain of Fort Bliss (Monger, 1995). The work built on the considerable USDA soil-geomorphic research in the Rio Grande Valley just to the west (e.g., Gile et al., 1965, 1966, 1981).

Likewise, the USDA soil surveys have been used for some geomorphic mapping, which has geoarchaeological potential. Areas with strongly contrasting parent materials and landforms are a key component in linking soil series to specific rock types, deposits, and geomorphic features (e.g., Lindholm, 1993, Lindholm, 1994a; Lindholm, 1994b). Brevik and Fenton (1999) used soil surveys to map late Pleistocene strandlines of Glacial Lake Agassiz in eastern North Dakota. As part of a geomorphological and geoarchaeological investigation of the National Tallgrass Prairie Preserve in the Flint Hills of east-central Kansas, Mandel (2006a) used the USDA soil survey to map the spatial pattern of Holocene and late Pleistocene alluvial lithostratigraphic units in Fox Creek valley. This was possible because certain soil series are associated with specific lithostratigraphic units in the Flint Hills region. Ultimately, a 1:24,000-scale map showing the geologic potential (high, medium, and low) for buried cultural deposits was generated based on the spatial pattern of the lithostratigraphic units (Mandel, 2006a: Figure 29).

Beyond the county soil surveys produced by the USDA, a wide variety of soil maps exists, produced in many different scales for an array of purposes by a wide range of agencies. Many of these maps probably have archaeological applications, especially the larger-scale ones (i.e., maps covering small areas). In the Netherlands, a soil survey produced at 1:10,000 proved useful in predicting likely site locations (beach ridges and natural levees) and site age because it was prepared by linking soil types to specific late Quaternary deposits and land forms (Dekker and De Weerd, 1973). The Soil Survey of Scotland (1981) was put to good use in a geoarchaeological context as part of a study of ancient land management in Orkney (Simpson, 1997). One phase of a soil series in the area was identified as a *plaggen* (see entry on Anthrosols in this volume) (Davidson and Simpson, 1984). The soil survey could, therefore, be used in a study of the origins of plaggen soils and their implications for land use in the region in the thirteenth to nineteenth centuries.

Soil surveys also have been carried out for expressly archaeological purposes with considerable success. In the Midwestern USA, soil surveys along alluviated valleys have been important components of some archaeological site prediction studies (e.g., Bettis, 1992; Mandel, 1992, 1994, 2006a; Stafford and Creasman, 2002; Gottsfield, 2009; Beeton and Mandel, 2011; West, 2012). The work entails (1) looking at the distribution of soil types (taxonomic great groups and soil series) and their parent materials (i.e., the sediments comprising the alluvial fill); (2) dating the sediments, soils, and associated landforms (typically stream terraces); (3) modeling the environmental evolution of the sediments and soils; and (4) using the resulting data to predict the location and age of archaeological sites, buried and at the surface, and to interpret the distribution of sites once surveys are completed. Not only are these surveys important for locating sites, but they can also indicate likely areas where sites



Soil Survey, Figure 1 Soils exposed in a streambank at 14SN106, one of three sites at the Kanorado Locality in northwestern Kansas. At all three sites, the Kanorado paleosol, which represents a buried Paleoindian-age landscape, contains Folsom and Clovis-age cultural deposits. In draws on the High Plains of western Kansas and eastern Colorado, the Kanorado paleosol typically occurs where the Goshen soil series is developed in alluvium underlying a low terrace. This relationship allows NRCS soil survey data to be used to target areas with high potential for buried Paleoindian cultural deposits.

will be absent, either because the sediments and landscapes likely to be associated with archaeological sites are missing or because the extant deposits and landforms are too young. A similar, and equally successful, approach to locating and interpreting sites, but at a longer time scale, based on mapping of soils and landforms was also carried out in Jordan (Cordova et al., 2005).

In a recent study, West (2012) developed a soil-based methodology for predicting the location of buried Paleoindian cultural deposits in small, intermittent streams, or draws, on the High Plains of western Kansas and eastern Colorado. Results of geomorphological investigations at the Kanorado locality in Middle Beaver Creek, a draw in northwestern Kansas, suggested that a buried soil – the Kanorado paleosol – typically occurs where the Goshen soil series is developed in alluvium underlying a low terrace (Figure 1) (Mandel et al., 2004; Mandel, 2008). The Kanorado paleosol is developed between ca. 14 and 10.4 ka (Cordova et al., 2011) and contains Clovis-age and Folsom cultural deposits (Mandel, 2015). West (2012) used the USDA-NRCS Soil Survey Geographic (SSURGO) database to map the distribution of the Goshen series throughout Middle Beaver Creek basin. He then examined stream cutbanks and cored areas where the Goshen series occurs. Based on the results of his ground truthing, 71 % of the localities with the Goshen series had a buried soil that fits the description of the Kanorado paleosol. Radiocarbon dating of soil organic matter confirmed that the buried soil is the same age as the Kanorado paleosol. Hence, the co-occurrence of the Goshen series and Kanorado paleosol is not a coincidence, and alluvial terraces mapped with the Goshen series have high potential for yielding stratified Paleoindian cultural deposits (West, 2012).

In southwestern Greece, soil mapping was a component of long-term investigations in and near Nichoria (McDonald and Rapp, 1972; Rapp and Aschenbrenner, 1978). The mapping was a traditional soil survey and provided relatively little data of archaeological significance. But the surveys did show significant differences in soil morphology (Alfisols and Inceptisols) in and near the field area (Yassoglou and Nobeli, 1972; Yassoglou and Haidouti, 1978). This difference in soil types was attributed to differences in landscape stability and soil age (Alfisols = older, more stable landscape; Inceptisols = younger, disturbed landscape) due to human impacts.

A survey designed expressly to identify relict arable soils was carried out on the Lofoten Islands of Norway (Simpson et al., 1998). Traditional field survey was combined with analysis of pollen cores to detect the onset of agriculture and examination of soil micromorphology in thin sections (see entry on Soil Micromorphology in this volume) to complement field evidence for agriculture or other human impacts.

In Britain, data derived from digital maps of both soils and surface geology provided information on groundwater levels, oxidation and reduction in soils, soil acidity, and soluble salts and salt content. These data have proven useful for understanding near-surface site preservation throughout the country (Ward et al., 2009).

Site-specific soil surveys have proven helpful in solving particular archaeological research questions. At the Altofts site, West Yorkshire, UK, an area identified as a henge (a circular or oval area enclosed by a bank and an internal ditch) was investigated to determine whether, in fact, it was a henge (Weston, 1996). In western Belize, soils provide insights into the location of Maya cacao orchards (Muhs et al., 1985). Cacao was one of the most important crops of the lowland Maya, but evidence of where the cacao was grown is rarely evident. In addition, cacao macrofossils are rarely preserved, and cacao sheds little pollen. Muhs et al. (1985) addressed the problem by mapping and analyzing soils at an ethnohistorically documented cacao-growing center and extrapolating to areas that may have produced cacao in antiquity.

Several site-focused soil surveys have helped resolve issues of site location and age. A soil survey around the ancient Bronze Age city of Harappa in Pakistan (Pendall and Amundson, 1990; Amundson and Pendall, 1991; Belcher and Belcher, 2000) used a soil-geomorphic approach to reconstruct the Holocene evolution of the landscape in the site area and to understand the relation of the site to the adjacent Ravi River. In a somewhat similar approach, Jones (1990) conducted soil surveys at a series of sites on the North Island of New Zealand. Using published, regional soil surveys combined with data from studies of local fluvial geomorphology, he was able to apply local soil data to estimate the maximum ages for construction of fortified settlements.

In sum, soil surveys can provide useful information in archaeological investigations, but it is important to recognize the limitations of the data presented in the surveys. Because soil surveys are generalized, they should be used only to establish initial impressions of soil-geomorphic relationships in a study area (Mandel and Bettis, 2001, 182). Detailed field investigations are required to confirm and elaborate on those impressions and to refine them to the scale (both spatial and temporal) needed by most archaeologists (Artz, 1985).

Bibliography

Almy, M. M., 1978. The archeological potential of soil survey reports. *The Florida Anthropologist*, **31**(3), 75–91.

Amundson, R., and Pendall, E., 1991. Pedology and late quaternary environments surrounding Harappa: a review and synthesis. In Meadow, R. H. (ed.), *Harappa Excavations 1986–1990: A Multidisciplinary Approach to Third Millennium Urbanism*. Madison: Prehistory Press. Monographs in World Archaeology, 3, pp. 13–27.

Artz, J. A., 1985. A soil-geomorphic approach to locating buried late Archaic sites in northeast Oklahoma. *American Archaeology*, **5**(2), 142–150.

Balster, C. A., and Parsons, R. B., 1968. *Geomorphology and Soils, Willamette Valley, Oregon*. Corvallis: Agricultural Experiment Station, Oregon State University. Special Report, 265.

Beeton, J. M., and Mandel, R. D., 2011. Soils and late-quaternary landscape evolution in the Cottonwood River basin, east-central Kansas: implications for archaeological research. *Geoarchaeology*, **26**(5), 693–723.

Belcher, W. R., and Belcher, W. R., 2000. Geologic constraints on the Harappa archaeological site, Punjab Province, Pakistan. *Geoarchaeology*, **15**(7), 679–713.

Bettis, E. A., III, 1992. Soil morphologic properties and weathering zone characteristics as age indicators in Holocene alluvium in the Upper Midwest. In Holliday, V. T. (ed.), *Soils and Landscape Evolution*. Washington, DC: Smithsonian Institution Press, pp. 119–144.

Bettis, E. A., III, and Benn, D. W., 1984. An archaeological and geomorphological survey in the central Des Moines River valley, Iowa. *Plains Anthropologist*, **29**(105), 211–226.

Brevik, E. C., and Fenton, T. E., 1999. Improved mapping of the Lake Agassiz Herman strandline by integrating geological and soil maps. *Journal of Paleolimnology*, **22**(3), 253–257.

Broderson, W. D., 1994. *From the Surface Down: An Introduction to Soil Surveys for Agronomic Use*, revised edition. Washington, DC: U.S. Department of Agriculture, Soil Conservation Service.

Buol, S. W., Southard, R. J., Graham, R. C., and McDaniel, P. A., 2011. *Soil Genesis and Classification*, 6th edn. Chichester: Wiley.

Butler, B. E., 1980. *Soil Classification for Soil Survey*. Oxford: Clarendon.

Cordova, C. E., Foley, C., Nowell, A., and Bisson, M., 2005. Landforms, sediments, soil development and prehistoric site settings in the Madaba-Dhiban Plateau, Jordan. *Geoarchaeology*, **20**(1), 29–56.

Cordova, C. E., Johnson, W. C., Mandel, R. D., and Palmer, M. W., 2011. Late quaternary environmental change inferred from phytoliths and other soil-related proxies: case studies from the central and southern Great Plains, USA. *Catena*, **85**(2), 87–108.

Davidson, D. A., and Simpson, I. A., 1984. The formation of deep topsoils in Orkney. *Earth Surface Processes and Landforms*, **9**(1), 75–81.

Dekker, L. W., and De Weerd, M. D., 1973. The value of soil survey for archaeology. *Geoderma*, **10**(1–2), 169–178.

FAO., 2006. World Reference Base for Soil Resources 2006: A Framework for International Classification, Correlation and Communication. Rome: Food and Agriculture Organization of the United Nations. World Soil Resources Report 103.

Gerig, A. J., 1985. *Soil Survey of the Clackamas County Area, Oregon*. Washington, DC: U. S. Department of Agriculture, Soil Conservation Service.

Gile, L. H., Peterson, F. F., and Grossman, R. B., 1965. The K horizon: a master soil horizon of carbonate accumulation. *Soil Science*, **99**(2), 74–82.

Gile, L. H., Peterson, F. F., and Grossman, R. B., 1966. Morphological and genetic sequences of carbonate accumulation in desert soils. *Soil Science*, **101**(5), 347–360.

Gile, L. H., Hawley, J. W., and Grossman, R. B., 1981. *Soils and Geomorphology in the Basin and Range Area of Southern New Mexico: Guidebook to the Desert Project*. Socorro: New Mexico Bureau of Mines and Mineral Resources. Memoir, 39.

Gottsfield, A. S., 2009. *Late-Quaternary Stratigraphy and Geoarchaeology of the Upper Neosho River Basin, East-Central Kansas*. Unpublished MA thesis, Lawrence, University of Kansas.

Hole, F. D., and Campbell, J. B., 1985. *Soil Landscape Analysis*. Totowa: Rowman and Allanheld.

Holliday, V. T., 2004. *Soils in Archaeological Research*. New York: Oxford University Press.

Holliday, V. T., McFadden, L. D., Bettis, E. A., III, and Birkeland, P. W., 2002. The soil survey and soil geomorphology. In Helms, D., Effland, A. B. W., and Durana, P. J. (eds.), *Profiles in the History of the U.S. Soil Survey*. Ames: Iowa State Press, pp. 233–274.

Johnson, W. C., and Logan, B., 1990. Geoarchaeology of the Kansas River Basin, central Great Plains. In Lasca, N. P., and Donahue, J. (eds.), *Archaeological Geology of North America*. Boulder: Geological Society of America. Centennial, Vol. 4, pp. 267–299.

Johnson, W. C., and Martin, C. W., 1987. Holocene alluvial-stratigraphic studies from Kansas and adjoining states of the east-central Plains. In Johnson, W. C. (ed.), *Quaternary Environments of Kansas*. Lawrence: Kansas Geological Survey. Kansas Geological Survey Guidebook Series, Vol. 5, pp. 109–122.

Jones, K. L., 1990. Settlement chronology on river terrace land forms: a New Zealand case study. *Geoarchaeology*, **5**(3), 255–273.

King, R. H., 1983. Soils and archaeological surveys: the case of the Canadian Palaepaphos survey project. In Keller, D. R., and Rupp, D. W. (eds.), *Archaeological Survey in the Mediterranean Area*. Oxford: British Archaeological Reports. British Archaeological Reports, International Series, 155, pp. 101–107.

Lindholm, R. C., 1993. Soil maps as an aid to making geologic maps, with an example from the Culpeper Basin, Virginia. *Journal of Geological Education*, **41**(4), 352–357.

Lindholm, R. C., 1994a. The value of soil maps to geologists: an acknowledgment. *Soil Survey Horizons*, **35**, 40–48.

Lindholm, R. C., 1994b. Information derived from soil maps: areal distribution of bedrock landslide distribution and slope steepness. *Environmental Geology*, **23**(4), 271–275.

Litwinionek, L., Johnson, E., and Holliday, V. T., 2003. The playas of the Southern high plains: an archipelago of human occupation for 12,000 years on the North American grasslands. In Kornfeld, M., and Osborn, A. J. (eds.), *Islands on the Plains: Ecological, Social, and Ritual Use of Landscapes*. Salt lake City: University of Utah Press, pp. 21–43.

Lovis, W. A., Jr., 1976. Quarter sections and forests: an example of probability sampling in the northeastern Woodlands. *American Antiquity*, **41**(3), 364–372.

Mandel, R. D., 1992. Soils and Holocene landscape evolution in central and southwestern Kansas: implications for archaeological research. In Holliday, V. T. (ed.), *Soils and Landscape Evolution*. Washington, DC: Smithsonian Institution Press, pp. 41–100.

Mandel, R. D., 1994. *Holocene Landscape Evolution in the Pawnee River Valley, Southwestern Kansas*. Lawrence: Kansas Geological Survey. Kansas Geological Survey Bulletin, 236.

Mandel, R. D., 1995. Geomorphic controls of the Archaic record in the Central Plains of the United States. In Bettis, E. A., III (ed.), *Archaeological Geology of the Archaic Period in North America*. Boulder: Geological Society of America. GSA Special Paper 297, pp. 37–66.

Mandel, R. D., 2006a. *Geomorphology, Quaternary Stratigraphy, and Geoarchaeology of Fox Creek Valley, Tallgrass Prairie National Preserve, Northeast Kansas*. Lawrence: Kansas Geological Survey. Kansas Geological Survey Open-File Report 2006–29.

Mandel, R. D., 2006b. The effects of late quaternary landscape evolution on the archaeology of Kansas. In Hoard, R. J., and Banks, W. E. (eds.), *Kansas Archaeology*. Lawrence: University Press of Kansas, pp. 46–75.

Mandel, R. D., 2008. Buried Paleoindian-age landscapes in stream valleys of the central Plains, USA. *Geomorphology*, **101**(1–2), 342–361.

Mandel, R. D., 2015. *Odyssey Archaeological Research Fund Report of Investigations, Summer and Fall, 2015*. Lawrence: Kansas Geological Survey, University of Kansas.

Mandel, R. D., and Bettis, E. A., III, 2001. Use and analysis of soils by archaeologists and geoscientists: a North American perspective. In Goldberg, P., Holliday, V. T., and Ferring, C. R. (eds.), *Earth Sciences and Archaeology*. New York: Kluwer/Plenum Publishers, pp. 173–204.

Mandel, R. D., Hofman, J. L., Holen, S., and Blackmar, J. M., 2004. Buried Paleo-Indian landscapes and sites on the high plains of northwestern Kansas. In Nelson, E. P. (ed.), *Field Trips in the Southern Rocky Mountains, USA*. Boulder: Geological Society of America. GSA Field Guide, 5, pp. 69–88.

Mausbach, M. J., and Wilding, L. P., 1991. *Spatial Variabilities of Soils and Landforms*. Madison: Soil Science Society of America. SSSA Special Publication, 28.

McDonald, W. A., and Rapp, G. R., Jr. (eds.), 1972. *The Minnesota Messinia Expedition: Reconstructing a Bronze Age Regional Environment*. Minneapolis: University of Minnesota Press.

Monger, H. C., 1995. Pedology in arid lands archaeological research: an example from southern New Mexico-western Texas. In Collins, M. E., Carter, B. J., Gladfelter, B. G., and Southard, R. J. (eds.), *Pedological Perspectives in Archaeological Research*. Madison: Soil Science Society of America. Special Publication, 44, pp. 35–50.

Muhs, D. R., Kautz, R. R., and MacKinnon, J. J., 1985. Soils and the location of cacao orchards at a Maya site in western Belize. *Journal of Archaeological Science*, **12**(20), 121–137.

O'Brien, M. J., Warren, R. E., and Lewarch, D. E. (eds.), 1982. *The Cannon Reservoir Human Ecology Project: An Archaeological Study of Cultural Adaptations in the Southern Prairie Peninsula*. New York: Academic.

Parsons, R. B., Balster, C. A., and Ness, A. O., 1970. Soil development and geomorphic surfaces, Willamette Valley, Oregon. *Soil Science Society of America Journal*, **34**(3), 485–491.

Pendall, E. G., and Amundson, R., 1990. Soil/landform relationships surrounding the Harappa archaeological site, Pakistan. *Geoarchaeology*, **5**(4), 301–322.

Plog, F., 1971. Some operational considerations. In Gumerman, G. J. (ed.), *The Distribution of Prehistoric Population Aggregates*. Prescott: Prescott college press. Prescott College Anthropological Reports, 1, pp. 45–54.

Rapp, G. R., Jr., and Aschenbrenner, S. E. (eds.), 1978. *Excavations at Nichoria in Southwest Greece. volume 1, Site Environs, and Techniques*. Minneapolis: University of Minnesota Press.

Saucier, R. T., 1966. Soil-survey reports and archaeological investigations. *American Antiquity*, **31**(3, pt 1), 419–422.

Shipman, J. A., 1997. *Soil Survey of the Lincoln County Area, Oregon*. Washington, DC: Natural Resources conservation Service.

Simonson, R. W., 1987. *Historical Aspects of Soil Survey and Soil Classification*. Madison: Soil Science Society of America (reprinted from Soil Survey Horizons).

Simonson, R. W., 1997. Evolution of soil series and type concepts in the United States. In Yaalon, D. H., and Berkowicz, S. (eds.), *History of Soil Science: International Perspectives*. Reiskirchen: Catena Verlag. Advances in GeoEcology, 29, pp. 79–108.

Simpson, I. A., 1997. Relict properties of anthropogenic deep top soils as indicators of infield management in Marwick, West Mainland, Orkney. *Journal of Archaeological Science*, **24**(4), 365–380.

Simpson, I. A., Bryant, R. G., and Tveraabak, U., 1998. Relict soils and early arable land management in Lofoten, Norway. *Journal of Archaeological Science*, **25**(12), 1185–1198.

Soil Survey of Scotland, 1981. *1:50,000 Soil Maps of Orkney: Orkney Mainland, Orkney Northern Isles and Orkney Hoy*. Aberdeen: Macaulay Institute for Soil Research.

Soil Survey Division Staff, 1993. *Soil Survey Manual* (revised). USDA Handbook, 18. Washington, DC: U.S. Department of Agriculture.

Sorenson, C. J., Sallee, K. H., and Mandel, R. D., 1987. Holocene and Pleistocene soils and geomorphic surfaces of the Kansas River valley. In Johnson, W. C. (ed.), *Quaternary Environments of Kansas*. Lawrence: Kansas Geological Survey. Kansas Geological Survey Guidebook Series, Vol. 5, pp. 93–102.

Stafford, C. R., and Creasman, S. D., 2002. The hidden record: late Holocene landscapes and settlement archaeology in the Lower Ohio River Valley. *Geoarchaeology*, **17**(2), 117–140.

Swanson, D. K., 1990. Landscape classes: higher-level map units for soil survey. *Soil Survey Horizons*, **31**, 52–54.

Voight, E. E., and O'Brien, M. J., 1981. The use and misuse of soils-related data in mapping and modeling past environments: an example from the central Mississippi River valley. *Contract Abstracts and CRM Archeology*, **2**, 22–35.

Ward, I., Smith, B., and Lawley, R., 2009. Mapping the archaeological soil archive of sand and gravel mineral reserves in Britain. *Geoarchaeology*, **24**(1), 1–21.

Warren, R. E., 1982a. The historical setting. In O'Brien, M. J., Warren, R. E., and Lewarch, D. E. (eds.), *The Cannon Reservoir Human Ecology Project: An Archaeological Study of Cultural Adaptations in the Southern Prairie Peninsula*. New York: Academic, pp. 337–368.

Warren, R. E., 1982b. Prehistoric settlement patterns. In O'Brien, M. J., Warren, R. E., and Lewarch, D. E. (eds.), *The Cannon Reservoir Human Ecology Project: An Archaeological Study of Cultural Adaptations in the Southern Prairie Peninsula*. New York: Academic, pp. 29–70.

Warren, R. E., and O'Brien, M. J., 1981. Regional sample stratification: the drainage class technique. *Plains Anthropologist*, **26**(93), 213–227.

Warren, R. E., and O'Brien, M. J., 1982. Holocene dynamics. In O'Brien, M. J., Warren, R. E., and Lewarch, D. E. (eds.), *The Cannon Reservoir Human Ecology Project: An Archaeological Study of Cultural Adaptations in the Southern Prairie Peninsula*. New York: Academic, pp. 71–84.

Warren, R. E., McDonnell, C. K., and O'Brien, M. J., 1981. Soils and settlement in the Southern Prairie Peninsula. *Contract Abstracts and CRM Archeology*, **2**, 36–49.

West, K. R., 2012. *A Soil-Based Methodology for Locating Buried Early Prehistoric Cultural Deposits in Draws on the High Plains of Eastern Colorado and Western Kansas*. Unpublished MA thesis, Lawrence, University of Kansas.

Weston, D., 1996. Soil science and the interpretation of archaeological sites: a soil survey and magnetic susceptibility analysis of Altofts 'Henge', Normanton, West Yorkshire. *Archaeological Prospection*, **3**(1), 39–50.

Wilding, L. P., and Drees, L. R., 1983. Spatial variability and pedology. In Wilding, L. P., Smeck, N. E., and Hall, G. F. (eds.), *Pedogenesis and Soil Taxonomy, I: Concepts and Interactions*. Amsterdam: Elsevier. Developments in Soil Science 11A, pp. 83–116.

Yaalon, D. H., and Berkowicz, S. (eds.), 1997. *History of Soil Science: International Perspectives*. Reiskirchen: Catena Verlag. Advances in GeoEcology 29.

Yassoglou, N. J., and Haidouti, C. F., 1978. Soil formation. In Rapp, G. R., Jr., and Aschenbrenner, S. E. (eds.), *Excavations at Nichoria in Southwest Greece. volume 1, Site Environs, and Techniques*. Minneapolis: University of Minnesota Press, pp. 31–40.

Yassoglou, N. J., and Nobeli, C., 1972. Soil studies. In McDonald, W. A., and Rapp, G. R., Jr. (eds.), *The Minnesota Messinia Expedition: Reconstructing a Bronze Age Regional Environment*. Minneapolis: University of Minnesota Press, pp. 171–176.

Cross-references

Anthrosols
Minnesota Messenia Expedition (MME)
Soil Geomorphology
Soils

SOILS

Vance T. Holliday[1], Rolfe D. Mandel[2] and E. Arthur Bettis III[3]
[1]Anthropology and Departments Geosciences, University of Arizona, Tucson, AZ, USA
[2]Department of Anthropology, University of Kansas, Lawrence, KS, USA
[3]Department of Earth and Environmental Sciences, University of Iowa, Iowa City, IA, USA

Introduction

Archaeologists generally realize that there is an important relationship between cultural deposits and associated soils. Yet, their understanding of what a soil is, as well as what soils can reveal about site formation processes, landscape development, and environments of the past, varies greatly. Although archaeologists should not be expected to have a complete grasp of pedology, they should be capable of recognizing and interpreting soils in an archaeological context in order to comprehend fully the record of the human past (Mandel and Bettis, 2001).

Soils are a part of the stage upon which humans evolved. As an integral component of most natural landscapes, soils also are an integral component of cultural landscapes. Furthermore, soils are indicators of the nature and history of the physical and human landscape, they record the impact of human activity, they are a source of food and fuel, and they reflect the environment and record the passage of time. Soils also affect the nature of the cultural record left to archaeologists. They are a "reservoir" for artifacts and other traces of human activity, encasing archaeological materials and archaeological sites. Soil forming processes also are an important component of site formation processes. Pedogenesis influences which artifacts, features, and environmental indicators (floral, faunal, and geological) are destroyed, which are preserved, and the degree of preservation. Most of these many aspects of soils are dealt with elsewhere (see the entry on Site Formation Processes in this volume).

A soil is a natural three-dimensional entity that is a type of weathering phenomenon occurring at the immediate surface of the earth in sediment and rock and serving as a medium for plant growth. Soil is the result of the interaction of climate, flora, fauna, and landscape position, all of which act on sediment or rock through time (modified from Schaetzl and Anderson, 2005, 9; Soil Science Society of America, 2008). The surface supporting soil development (i.e., the rock or sediment in which the soil forms) is referred to as *parent material*. This concept of soil has important corollaries (Holliday, 2004, 2–3; see also Schaetzl and Thompson, 2015, 6–7):

1. Soils form in, or represent an alteration by weathering of, sediments and rocks over time, i.e., soils are a type of surface weathering phenomenon.
2. Pedogenesis includes some interaction with flora and fauna and the accumulation of organic matter.
3. There is some movement or redistribution (typically downward) of clastic, biochemical, and ionic soil constituents (e.g., clay, organic carbon, iron, aluminum, and manganese compounds, as well as calcium carbonate in ionic solution).
4. Soils are an intimate component of the landscape; they form on relatively stable land surfaces and are approximately parallel to the land surface.
5. Soils are dynamic components of the ecosystem representing the interface of the atmosphere, the biosphere, and the geosphere.
6. Soils are extremely complex systems.

Soils are laterally extensive over entire landscapes. They form across various landforms and in a variety of parent materials, and they vary in a predictable manner according to changes in erosion, deposition, drainage, vegetation, and age of the landscape. Soils also vary as the microclimate and macroclimate vary. In buried soils (see below and the entry on Soil Stratigraphy in this volume), this predictability allows them to be traced laterally over varying paleotopography. In contrast, individual layers of sediment are confined to particular depositional environments; they will thin to nothing as one moves away from that environment (Mandel and Bettis, 2001, 180).

Soil science is a broad discipline that involves both the earth and agricultural sciences and includes the study of soil formation, classification, mapping, chemistry, mineralogy, physics, biology, and fertility (Soil Science Society of America, 2008). The principal subfields of soil science most widely applied in archaeology and geoarchaeology are pedology, soil geomorphology, and soil chemistry.

Pedology is the study of soils as three-dimensional bodies intimately related to the landscape, and it focuses on their morphology, genesis, and classification. Soil geomorphology is the study of relationships between soils and landscapes (e.g., Ruhe, 1956; Ruhe, 1965; Daniels and Hammer, 1992; Gerrard, 1992; Birkeland, 1999) (see the entry on Soil Geomorphology in this volume). In its broadest sense, soil geomorphology considers the influence of climate, flora, fauna, topography, and geologic substrate on pedogenesis, all operating over time (e.g., Birkeland, 1999). Soil chemistry deals with the chemical makeup of soils and how it relates to agricultural productivity (see the entry on *Anthrosols* in this volume). Soil chemistry has long been studied both by soil scientists and archaeologists for clues to human impact on the landscape, especially for reconstructing agricultural activity and for detecting human occupation (e.g., Arrhenius, 1931; Solecki, 1951; Cornwall, 1958; Arrhenius, 1963; Berlin et al., 1977; Eidt, 1977; Eidt, 1984; Eidt, 1985).

All of these subdisciplines of soil science share important perspectives with archaeology. Soil geomorphology focuses on reconstructing landscapes, and pedology and soil chemistry deal with soils as resources. The agriculture tradition in soil science provides a unique perspective for archaeologists who are trying to understand the origins, evolution, and characteristics of agriculture. Pedologists can also provide important insights into understanding human impacts on soils, such as soil erosion. Soil stratigraphy and soil chemistry rather than pedology and soil geomorphology are perhaps the best-known and oldest applications of soil science in archaeology (Holliday, 2004).

Soil genesis

Soil genesis or *pedogenesis* is a complex system of physical, chemical, and biological processes that alter parent material (geologic sediment or rock). These processes are driven by a broad array of environmental variables that operate over time. Soil scientists, geologists, and geographers have attempted to describe and model the processes of soil formation, the factors that drive the processes, and the evolution of soils as their landscapes evolve (summarized by Smeck et al., 1983; Johnson and Watson-Stegner, 1990; Gerrard, 1992, 1–50, 217–220; Schaetzl and Anderson, 2005, 295–346; Minasny et al., 2008). The task is a difficult one due to the complex and variable sets of processes responsible for soil development and the fact that these processes operate in a historical framework. Several of the resulting approaches have, however, proven useful for conceptualizing pedogenesis and, more importantly, for interpreting soils in a geomorphic/geoarchaeological context. In addition to understanding soil-forming processes for interpreting soil profiles, an understanding of soil formation processes is crucial for interpreting archaeological site formation. The conceptual approaches particularly useful in soil-geomorphic and geoarchaeological research are summarized below.

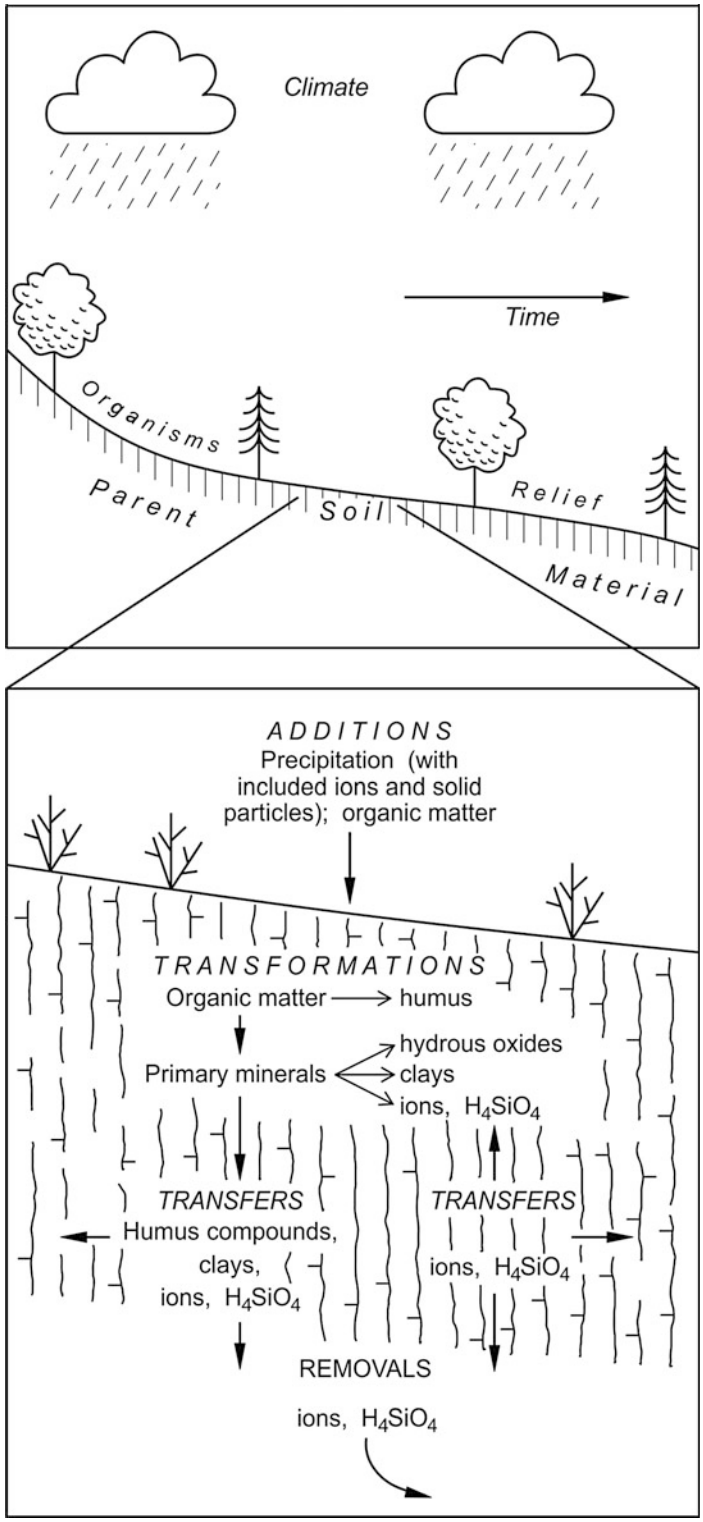
Soils are the result of biogeochemical processes determined by and driven by the ecosystem (following Schaetzl and Anderson, 2005, 3–4, 295–296; Buol et al., 2011, 11–16, 85–151). This relationship is more simply described as “internal soil forming processes” driven by “external soil forming factors” (after Buol et al., 1989). A useful approach to categorizing the many and varied internal soil forming processes responsible for pedogenesis is the multiple process model of Simonson (1959, 1978), who grouped the internal pedogenic processes into four categories: additions (e.g., water and organic matter), losses (e.g., leaching of carbonate), transfers (e.g., clay and iron illuviation), and transformations (e.g., organic residues decomposing to form humus) (Table 1; Figure 1).

The presence, absence, or degree of activity by these internal processes is a function of the complex interaction of external environmental factors. Consideration of these factors produced the “state factor” approach to soil genesis (Jenny, 1941; Jenny, 1980), which has been successfully applied in soil geomorphology (e.g., Birkeland, 1999) and has had many applications in archaeology (e.g., Holliday, 2004). Jenny (1941, 1980), following the work of many others (see Johnson and Hole, 1994; Tandarich and Sprecher, 1994 for a historical perspective), defined the state factors of soil formation (Figure 1 above) as climate (*C*), organisms (flora and fauna) (*O*), relief (or landscape setting) (*R*), parent material (*P*), and time (*T*) (the “clorpt” factors). There are also unspecified factors of local or minor importance (e.g., dust fall, groundwater fluctuations). Jenny (1941, 1980) proposed studying the variation in a soil as a function of one factor, keeping the other factors constant or accounted for. For example, variation in soils due to differences in climate could be studied by keeping all factors except climate constant. A group of soils forming as a function of any one state factor are called sequences (*climosequence*, *biosequence*, *toposequence*, *lithosequence*, *chronosequence*). The state factor approach to the study of soil genesis is not without criticism, which is summarized by Birkeland (1999, 144–145), Johnson and Watson-Stegner (1990), and Gerrard (1992, 3–7). In particular, Paton et al. (1995) attempt to overturn what they see as the “clorpt paradigm.”

Soils, Table 1 Soil forming processes, grouped according to Simonson's fourfold classification[a]

Process	Fourfold categorization[b]	Brief definition
Eluviation	3 hz	Movement of material out of a portion of a soil profile as in an albic horizon
Illuviation	3 hz	Movement of material into a portion of soil profile as in an argillic or spodic horizon
Leaching (*Depletion*)	2	General term for washing out or eluviating soluble materials from the solum
Enrichment	1	General term for addition of material to a soil body
Erosion	2 hp	Removal of material from the surface layer of a soil
Cumulization	1 hp	Eolian, hydrologic, and human-made additions of mineral particles to the surface of a soil solum
Decalcification	3 hz	Reactions that remove calcium carbonate from one or more soil horizons
Calcification	3 hz	Processes including accumulation of calcium carbonate in Bk and possibly other horizons of a soil
Salinization	3 hz	Accumulation of soluble salts such as chlorides, sulfates, and bicarbonates of sodium, calcium, magnesium, and potassium in salic horizons
Desalinization	3	Removal of soluble salts from salic soil horizons
Alkalization (*Solonization*)	3 hz	Accumulation of sodium ions on the exchanges sites in a soil
Dealkalization (*Solodization*)	3	Leaching of sodium from natric horizons
Lessivage	3 hz	Mechanical migration of small mineral particles from the A to the B horizons of a soil, producing B horizons relatively enriched in clay as in argillic horizons
Pedoturbation	3 hp	Biologic, physical (freeze-thaw and wet-dry cycles) churning and cycling of soil materials, thereby homogenizing the solum in varying degrees
Podzolization	3,4 hz	Chemical migration of aluminum and iron and/or organic matter, resulting in the concentrations of silica (i.e., silication) in the layer eluviated
Desilication (*Ferrallitization*, *Ferritization*, *Allitization*)	3,4 hz	Chemical migration of silica out of the soil solum and thus the concentration of sesquioxides in the solum (e.g., goethite, gibbsite), with or without formation of ironstone (laterite; hardened plinthite) and concretions
Resilication	4	Formation of kaolinite from gibbsite in presence of excess H_4SiO_4 (silicic acid) in solution or formation of smectite from kaolinite in presence of large amounts of H_4SiO_4 at higher pH values
Decomposition	4	Breakdown of mineral and organic materials
Synthesis	4	Formation of new particles of mineral and organic species
Melanization	1,3 hz	Darkening of light-colored, unconsolidated, initial materials by admixture of organic matter (as in a dark colored A horizon)
Leucinization	3 hz	Paling of soil horizons by disappearance of dark organic materials either through transformation to light-colored ones or through removal from the horizons
Littering	1	Accumulation on the mineral soil surface of organic litter and associated humus to a depth of less than 30 cm
Humification	4	Transformation of raw organic material into humus
Paludization	4 hp	Processes regarded by some workers as geogenic rather than pedogenic, including the accumulation of deep (>30 cm) deposits of organic matter as in mucks and peats (Histosols)
Ripening	4 hz	Chemical, biological, and physical changes in organic soil after air penetrates previously waterlogged material
Mineralization	4	Release of oxide solids through decomposition of organic matter
Braunification; *Rubification*; *Ferrugination*	3,4 hz	Release of iron from primary minerals and the dispersion of particles of iron oxides or oxyhydroxides in increasing amounts. Progressive oxidation or hydration of the iron colors the soil mass brownish, reddish brown, and red colors, respectively
Gleization	3,4 hp	Reduction of iron under anaerobic soil conditions, with the production of bluish to greenish gray matrix colors, with or without yellowish brown, brown, and black mottles, and ferric and manganiferous concretions
Loosening	4	Increase in volume of voids by activity of plants, animals, and humans and by freeze-thaw or other physical processes and by removal of material by leaching
Hardening	4	Decrease in volume of voids by collapse and compaction and by filling of some voids with fine earth, carbonates, silica, and other materials

[a]From Buol et al. (1997, Table 3.1)
[b]Soil forming processes: 1 Addition; 2 Removal; 3 Translocation; 4 Transformation; "hz" indicates processes that promote horizonation; "hp" indicates processes that promote haploidization (destruction of soil horizons)



Soils, Figure 1 Schematic illustration showing the relationship of the five external (or environmental) factors of soil formation (*above*) to the internal processes of soil genesis (Table 1) (Modified from Holliday, 2004, Figure 3.1).

At the most general level, the state factors represent natural conditions and do not deal with the processes that form soils, but instead they describe co-occurrences of state factors and specific soil properties. In archaeology and other areas of Quaternary research, the external factors are often the object of concern, and soils can be a means of reconstructing them; this means that soil properties are used as proxies to reconstruct former environmental conditions. The state factor approach also tends to treat the factors individually as independent variables, although they always act together, such as climate and biota. The time factor is the only truly independent variable, but the passage of time in and of itself does not form a soil; it is the historical framework in which the other factors operate.

The factors of soil formation generally of most concern in archaeology are time and environment (which includes climate and vegetation). State factor analysis examines soils to (1) determine the effects of climate and organisms and (2) determine how soils vary as a function of time. The resulting data then can be applied to soils in similar contexts as a means of environmental reconstruction or for estimating the age of deposits. An understanding of soil variability as a function of topographic position or parent material variation, which also can be investigated via state factor analysis, may also be important in reconstructing local environments and soil stratigraphy.

The state factor approach in a geoarchaeological context is further complicated by consideration of human activity as another factor of soil formation (Bidwell and Hole, 1965; Amundson and Jenny, 1991). For example, people have altered the biotic factor by removing forests and replacing them with farm crops; they have modified the topographic factors by digging canals, constructing terraced fields, or forming tells; and they have produced new soil types–anthrosols (see the entry on *Anthrosols* in this volume).

Soil profiles and horizons

A *soil profile* is the vertical arrangement of soil horizons, typically seen in a two-dimensional exposure down to and including the parent material. This series of layers is similar to a standard archaeological profile that may exhibit one or more soils. The *pedon* is the smallest body of one kind of soil large enough to represent the nature and arrangement of horizons (Soil Survey Division Staff, 1993, 18). Essentially, the pedon is the soil profile in three dimensions–a conceptual unit of soil defined for sampling purposes (see Schelling, 1970, 170; Soil Survey Staff, 1999, 10–14; Schaetzl and Anderson, 2005, 33–35; Buol et al., 2011, 30–31, 36).

Soil horizons are zones within the soil (i.e., subdivisions of the soil) that are parallel to the land surface and have distinctive physical, chemical, and biological properties. Soil horizons result from mineral alteration; additions of organic matter; leaching of soluble materials; and translocation of fine particles, humus, and chemical compounds. Together, a sequence of genetically related horizons produces a soil profile. Soil profiles vary due to the complex interaction of climate, the biota living on and in the soil, the nature of the soil parent material, landscape position, and the age of the landscape (i.e., the soil forming factors).

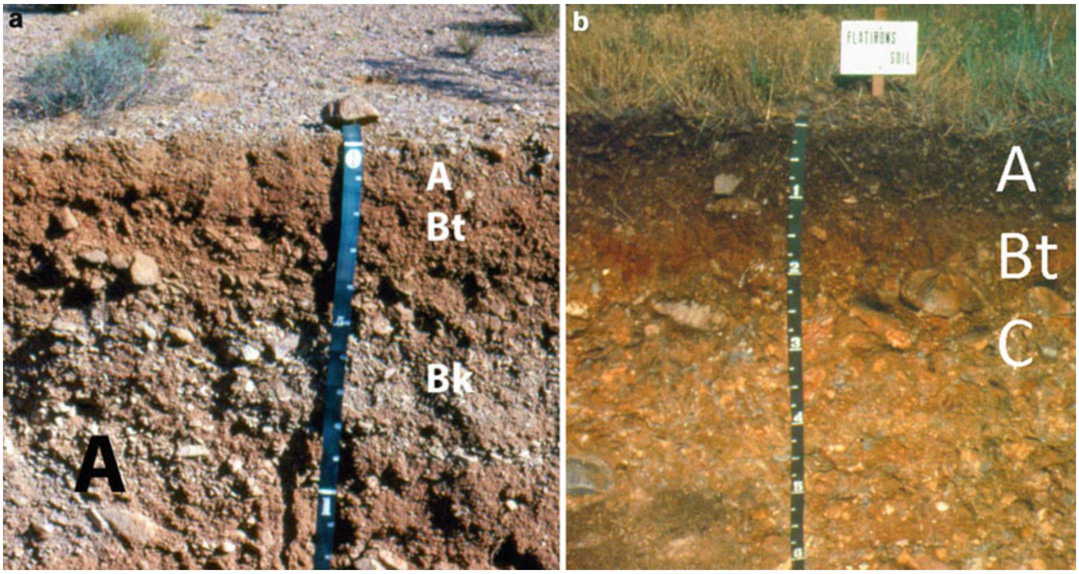
Soil horizons are the most obvious features of soils in the field because of their unique physical and chemical characteristics, such as soil structure and color (Figure 2a and b). Moreover, the development of soil horizons is a characteristic of soils unique among geomorphic processes and features. The ability to recognize soil horizons is a crucial first step in developing the ability to recognize soils. The visual distinctness of soil horizons and soils is one of the principal reasons they have long been used as stratigraphic markers. Careful scrutiny and description of soil profiles and horizons are critical elements of pedology and field geoarchaeology, and they require considerable training and practice to accomplish effectively.

Soil horizon nomenclature includes a few master or major horizons (the well-known A-B-C sequence), a considerable number of subhorizon symbols that act as modifiers of the master horizons, and additional descriptive terminology (Table 2). This system is fully explained by the Soil Survey Division Staff (1993; http://soils.usda.gov/technical/manual/).

Distinguishing soil from sediment

Archaeologists and soil geomorphologists alike must distinguish between deposits that are a product of sedimentary processes and those that are indicative of secondary alterations related to weathering at a land surface (i.e., soil formation). This distinction is important because in most cases a soil signifies a break in deposition; hence, it is an indicator of a relatively stable land surface (i.e., an often lengthy hiatus in sedimentation). The zone of soil formation (depth from the ground surface within which a soil develops) represents a significant time interval during which human activities can be recorded. This aspect distinguishes a soil from adjacent nonsoil deposits.

Many factors interplay to produce the characteristics of soils, but as noted above, one characteristic all soils have in common is a vertical sequence of genetically related horizons produced by soil-forming processes acting on geologic materials over time. The concept that soil horizons require the passage of some duration of time to form is one of the most fundamental and significant aspects of pedology in archaeology (Holliday, 1990, 530). Another important consideration is that soil development requires not only time but also a relatively stable landscape, one that is neither rapidly aggrading nor eroding (Catt, 1986, 166–167). Exceptions are bogs and marshes, where organic soils (histosols) form as a result of the accumulation of organic matter. Also, some soils, especially those on floodplains and toeslopes (gently inclined bottom of valley slopes), may receive influxes of parent material



Soils, Figure 2 (**a**) A moderately expressed soil formed in Holocene alluvium of the Rio Grande valley in semiarid southern New Mexico. The A horizon has very little organic matter owing to the low biological productivity. The Bk horizon illustrates the early stages of calcium carbonate accumulation. Scale in centimeters (Photo by Vance T. Holliday). (**b**) A strongly expressed soil formed under grassland in middle Pleistocene alluvium on the Great Plains of eastern Colorado. Scale in feet (Photo by Vance T. Holliday).

while pedogenesis is underway; that is, soil formation and deposition proceed concurrently and form cumulic soils (Nikiforoff, 1949; Birkeland, 1999). Disregarding these exceptions, the presence of a soil indicates that the landscape has been relatively stable for a period of time. In general, landscapes that have been stable for long periods have soils that are better expressed than those that have been stable for shorter periods, all other soil-forming factors being equal.

A soil in a stratigraphic sequence, whether at the surface or in a buried context, indicates a hiatus between depositional events. Holliday (1992, 103) stressed that, in such a sequence, "the sediment, which is the parent material for the soil, may have accumulated rapidly or slowly, but a significant period of nondeposition had to occur for the soil to form." Although large volumes of sediment may be deposited instantaneously, as with a debris flow, soil formation usually requires at least a century, or several centuries, and commonly millennia (Holliday, 1992; Birkeland, 1999).

In archaeological investigations, consideration of landscape stability, as indicated by soil development, is important in locating cultural deposits, interpreting artifact associations and contexts, defining site stratigraphy, reconstructing the depositional and landscape history, and establishing cultural chronologies. The first step is identifying which parts of the sedimentary deposits present in the site or study area have been modified as a result of soil formation. While this can be a fairly straightforward task, it often becomes complicated when pedogenically unaltered deposits have properties that mimic some properties of soils.

The first requirements in the recognition of a soil are identifying soil horizons and learning how to differentiate between soil horizons and sedimentary deposits that show soil-like properties (see the section on soil profiles above). Soil horizons often parallel a land surface, and they have distinctive properties that result from the complex interactions among many physical, chemical, and biological processes acting on surficial materials over time. The nature and magnitude of the influence of these processes, and the resulting properties of soils, are in large part controlled by various environmental factors. Both soils and unlithified geologic materials that are not soils can be described according to the following properties: color, texture, consistency, soil structure (or lack thereof), cutans (coatings), nodules or concretions, voids, reaction to hydrochloric acid (carbonate content), boundary characteristics, and horizon continuity. Specifics on the nomenclature for describing soil horizons and surficial materials are provided by Birkeland (1999), Soil Survey Staff (1999), Schoeneberger et al. (2002), Buol et al. (2011), and Schaetzl and Thompson (2015).

Distinguishing soil from sediments on the basis of the presence or absence of horizons is not always a simple procedure. For example, organic- or clay-rich alluvium that has not been modified by pedogenesis sometimes exhibits properties that mimic those of A and B horizons of soils, respectively. Several criteria may be used to discriminate a soil horizon from a depositional unit in an

Soils, Table 2 General definitions of soil horizons used in the USA[a]

Soil master horizons

O horizon or layer: Horizons or layers dominated by organic material. Some consist of undecomposed or partially decomposed litter, such as leaves, needles, twigs, moss, and lichens, that were deposited on the surface; they may be on top of either mineral or organic soils. Other O layers are organic materials that were deposited under saturated conditions and have decomposed to varying stages

A horizon: Mineral horizon that formed at the surface or below an O horizon, and that exhibits (1) obliteration of all or much of the original rock structure, and (2) an accumulation of humified organic matter intimately mixed with the mineral fraction

E horizon: Mineral horizon characterized by the loss of silicate clay, iron, aluminum, or some combination of these, leaving a concentration of sand and silt particles behind. This horizon exhibits obliteration of all or much of the original rock structure. An E horizon is usually lighter in color than an overlying A horizon and an underlying B horizon

B horizon: Horizon that forms below an A, E, or O horizon and is characterized by the obliteration of all or much of the original rock structure and shows one or more of the following: (1) illuvial concentration of silicate clay, iron, aluminum, humus, carbonates, gypsum, or silica, alone or in combination (brought down from overlying horizons by the action of water); (2) evidence of the removal of carbonates; (3) coatings of sesquioxides that make the color of the horizon conspicuously lower in value, higher in chroma, or redder in hue (Munsell color descriptors) than overlying and underlying horizons without apparent illuviation of iron; or (4) alteration that forms silicate clay, or liberates oxides, or both, and that forms granular, blocky, or prismatic structure

C horizon or layer: Horizon or layer, excluding hard bedrock, that is little affected by pedogenic processes and lacks the properties of O, A, E, or B horizons

R layers: Hard (minimally weathered) bedrock

Horizons dominated by properties of one master horizon but having subordinate properties of another. Two capital letter symbols are used: AB, EB, BE, or BC. The master horizon symbol is given first and designates the horizon whose properties dominate among the transitional properties (e.g., an AB horizon has characteristics of both an overlying A horizon and an underlying B horizon, but it is more like the A than the B)

Horizons in which distinct parts have recognizable properties of the two kinds of master horizons indicated by the capital letters. The two capital letters are separated by a virgule (/, or forward slash): E/B, B/E, or B/C. Most of the individual parts of one of the components are surrounded by the other

Subhorizons or subordinate horizons of the master horizons

a *Highly decomposed organic material*: Used with "O" to indicate the most highly decomposed of the organic materials

b *Buried soil or horizon*: Used in mineral soils to indicate identifiable buried horizons with major genetic features that were formed before burial. Genetic horizons may or may not have formed in the overlying material, which may be either like or unlike the assumed parent material of the buried soil

c *Concretions or nodules*: Indicate a significant accumulation of cemented concretions or nodules. The cementing agent is not specified except it cannot be silica. This symbol is not used if concretions or nodules are dolomite or calcite or more soluble salts, but it is used if the nodules or concretions are enriched in minerals that contain iron, aluminum, manganese, or titanium

e *Organic material of intermediate decomposition*: Used with "O" to indicate organic materials of intermediate decomposition

f *Frozen soil*: Indicates that the horizon or layer contains permanent ice. Symbol is not used for seasonally frozen layers or for "dry permafrost" (material that is colder than O° C but does not contain ice)

g *Strong gleying*: Indicates either that iron has been reduced and removed during soil formation or that saturation with stagnant water has preserved a reduced state. Most of the affected layers reveal a chroma of 2 or less and many have redox concentrations. The low chroma can be the color of reduced iron or the color of uncoated sand and silt particles from which iron has been removed. Symbol "g" is not used for soil materials of low chroma, such as some shales or E horizons, unless they have a history of wetness. If "g" is used with "B," pedogenic change in addition to gleying is implied. If no other pedogenic change in addition to gleying has taken place, the horizon is designated Cg

h *Illuvial organic matter*: Used with "B" to indicate the accumulation of illuvial, amorphous, dispersible organic matter-sesquioxide complexes. The symbol "h" is also used in combination with "s" as "Bhs" if the amount of sesquioxide component is significant but value and chroma of the horizon are 3 or less

i *Slightly decomposed organic material*: Used with "O" to indicate the least decomposed of the organic materials

k *Carbonates*: Accumulation of calcium carbonate

m *Cementation or induration*: Continuous or nearly continuous cementation. If the horizon is cemented by carbonates, "km" is used; if by silica, "qm"; if by iron, "sm"; if by gypsum, "ym"; if by both lime and silica, "kqm"; if by salts more soluble than gypsum, "zm"

n *Sodium*: Accumulation of exchangeable sodium

p *Plowing or other disturbance*: Disturbance of the surface layer by mechanical means, pasturing, or similar uses. A disturbed organic horizon is designated Op. A disturbed mineral horizon is designated Ap even though it was clearly once an E, B, or C horizon

q *Silica*: Accumulation of secondary silica

r *Weathered or soft bedrock*: Used with "C" to indicate root restrictive layers of soft bedrock or saprolite, such as weathered igneous rock; partly consolidated soft sandstone; siltstone; and shale. Excavation difficulty is low or moderate

s *Illuvial accumulation of sesquioxides and organic matter*: Used with "B" to indicate the accumulation of illuvial, amorphous, dispersible organic matter-sesquioxide complexes if both the organic matter and sesquioxide components are significant and the value and chroma of the horizon is more than 3. The symbol is also used in combination with "h" ("Bhs") if both the organic matter and sesquioxide components are significant and the value and chroma are 3 or less

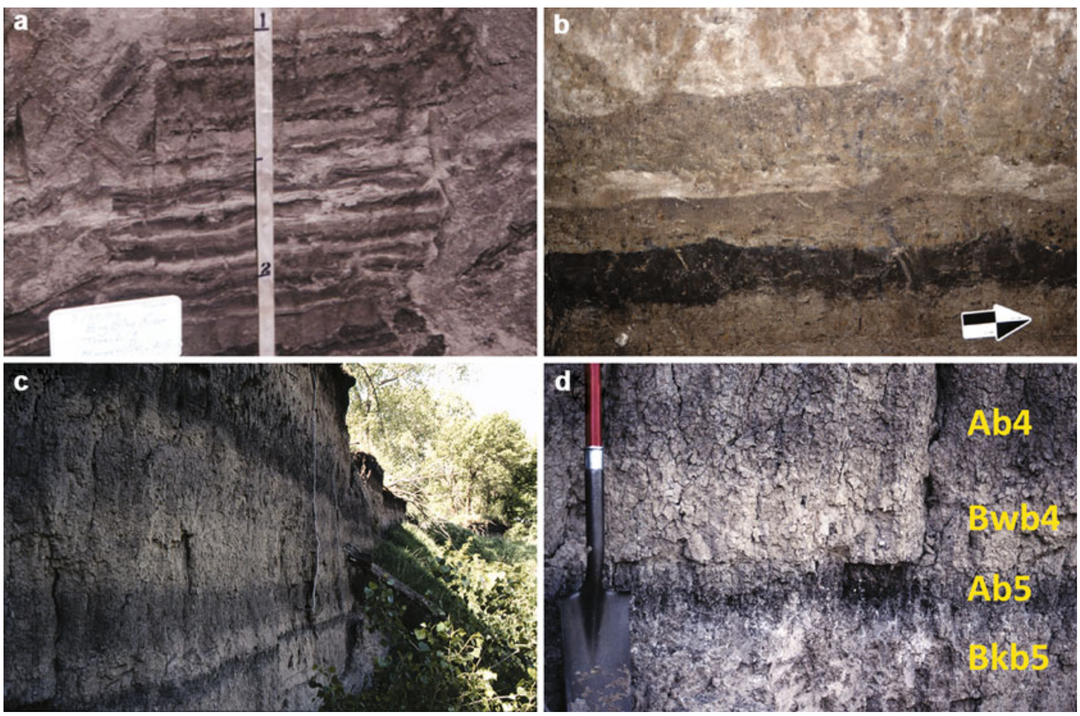
ss *Slickensides*: Presence of slickensides or sides of fault cracks, which result directly from the swelling of clay minerals and shear failure, commonly at angles of 20–60° above horizontal

t *Silicate clay*: Accumulation of silicate clay translocated within the horizon or moved into the horizon by illuviation, or both. At least some part should show evidence of clay accumulation in the form of coatings on surfaces of peds or in pores, or as lamellae ("clay bands"), or bridges between mineral grains

Soils, Table 2 (Continued)

v *Plinthite*: Presence of iron-rich, humus-poor, reddish material that is firm or very firm when moist and that hardens irreversibly when exposed to the atmosphere and to repeated wetting and drying
w *Development of color or structure*: Used with "B" to indicate the development of color or structure, or both, with little or no apparent illuvial accumulation of material
x *Fragipan*: Genetically developed layers that have a combination of firmness, brittleness, very coarse prisms with few to many bleached vertical faces, and commonly higher bulk density than adjacent layers
y *Gypsum*: Accumulation of gypsum
z *Salts more soluble than gypsum*: Accumulation of salts more soluble than gypsum

Combinations of symbols: A B horizon that is gleyed or that has accumulations of carbonates, sodium, silica, gypsum, salts more soluble than gypsum, or residual accumulation of sesquioxides carries the appropriate symbol–g, k, n, q, y, z, or o. If illuvial clay is also present, "t" precedes the other symbol, for example, Btg
[a]Modified from Soil Survey Division Staff (1993, 118–126). These symbols are used for describing soils in the field. For more complete definitions, see Buol et al. (1997), Birkeland (1999), Schoeneberger et al. (2002), or Soil Survey Division Staff (1993)



Soils, Figure 3 (**a**) Stratified modern alluvium beneath a floodplain. The dark, organic-rich flood drapes could be confused with buried A horizons. (**b**) The lower boundaries of the individual beds of alluvium, including the dark flood drapes, are abrupt and wavy. Hence, the flood drapes are not A horizons. The photo scale is 20 cm long. (**c**) Stratified early and middle Holocene alluvial fan deposits that have been altered by pedogenesis, as indicated by multiple buried soils developed at the top of the upward-fining sequences. (**d**) Note the smooth, gradual boundaries between the (**a**) and (**b**) horizons of the buried soils, compared to the abrupt, wavy boundaries separating flood drapes in (**a**) and (**b**) (Photos by Rolfe Mandel).

alluvial setting. To illustrate, the lower boundary of an A or B horizon is usually clear, gradual, or diffuse, rather than abrupt or wavy (Figure 3). Pedogenically unaltered clay- and organic-rich depositional layers often have abrupt and wavy boundaries or graded bedding produced by sedimentary processes. As bioturbation and other soil-forming processes affect the deposits, the abrupt boundaries that separate individual beds are obliterated.

Micromorphological studies (see the entries on Soil Micromorphology and Microstratigraphy in this volume) may help distinguish soil horizons from sedimentary zones in these situations by identifying fabrics indicative of mixing, soil-forming processes, or sedimentary processes (Courty et al., 1989; Courty, 1992).

Soil structure, which is the shape of soil aggregates (peds), can be used to distinguish organic-rich sedimentary deposits from A horizons of soils. Flood drapes, which tend to be clayey and enriched with organic matter, often contain clay minerals that shrink and swell with drying and wetting. The shrinking and swelling of these minerals gives the dark alluvium an angular blocky "structure" that may be misinterpreted as having formed by processes associated with a relatively stable land surface during a hiatus in sedimentation. An A horizon, however, typically has granular structure produced by the activity of worms and other soil organisms in this biologically active zone of the soil. In buried soils, the granular structure may be transformed into blocky types of structure during compaction, but evidence for the former A horizon may include greater porosity or granular aggregates that can be detected only in thin section via micromorphology (Courty et al., 1989; Courty, 1992). Patterns of rooting and burrowing also provide useful information for identifying former land surfaces and for distinguishing soils and unaltered sediments. Unaltered sediments are usually capable of supporting plant life and often become burrowed, but surfaces stable enough for soils to form are subject to more intensive rooting and potentially more burrowing activity simply because they represent more time per volume than unaltered deposits. The upper horizon of a soil, therefore, should be more heavily rooted, especially with fine roots, and contain more evidence for bioturbation than unaltered deposits. Because of the dark color of many soil surface horizons, and the rate of bioturbation and the small scale of many bioturbators, such as worms and ants, much of the conclusive rooting- and burrowing-pattern evidence for distinguishing soil horizons from unaltered deposits is at the microscopic scale (Courty, 1992).

In arid and semiarid regions, deposits that have been affected by nonpedogenic accumulations of calcium carbonate can be easily confused with calcic soils (Mandel and Bettis, 2001). For example, laterally flowing, $CaCO_3$-rich groundwater often forms calcretes that are misidentified as soils with petrocalcic horizons (Machette, 1985). Development of a groundwater calcrete is a nonpedogenic process that occurs when calcium-charged groundwater discharges onto a stream bottom or reaches a near-surface position where calcium is concentrated by evaporation. Supersaturation of calcium causes precipitation of $CaCO_3$ and subsequent cementation of relatively porous sands and gravels (Machette, 1985). Further complicating matters, surface runoff may add or redistribute the $CaCO_3$, producing laminar zones that resemble laminar petrocalcic horizons (Bachman and Machette, 1977). Nevertheless, with careful field observations and micromorphological analyses, it is possible to distinguish groundwater calcretes from calcic soils. For example, groundwater calcretes are often strongly indurated to depths of 10 m or more (Machette, 1985). Petrocalcic horizons, however, are rarely more than several meters thick. When viewed in thin section, groundwater calcretes typically consist of simple cement fills enclosing clasts with grain-to-grain contact, whereas the cement of petrocalcic horizons is micritic and replaces or surrounds scattered detrital grains that appear to float in a matrix of carbonate (Mann and Horowitz, 1979; Machette, 1985; Arakel, 1986; Jacobsen et al., 1988). Also, groundwater calcretes generally lack the horizonation and morphological structures common in calcic soils (Bachman and Machette, 1977; Wright, 1982; Machette, 1985; Allen, 1986).

In an archaeological investigation, it is important to distinguish between a groundwater calcrete and a petrocalcic horizon because of the temporal, soil-stratigraphic, and environmental implications inherent in either identification. Groundwater calcretes form over the course of tens to hundreds of years, they are not products limited to periods of landscape stability, and they develop in a wide range of environments (humid to arid). Petrocalcic horizons, however, require thousands of years of carbonate accumulation in relatively stable arid or semiarid soil-forming environments (Gile and Hawley, 1966; Gile et al., 1966; Gile and Grossman, 1979; Birkeland, 1999; Schaetzl and Thompson, 2015, Figure 13.52).

In some situations, sandy C horizons may be confused with albic (E) horizons of soils. This usually occurs where a light-colored sandy C horizon lies beneath an A horizon and above a truncated Bt horizon. Such confusion may seriously compromise the interpretation of the soil stratigraphy, paleoenvironment, and age of an archaeological site. An E horizon is a product of intensive leaching (eluviation, or the downward transport of soil materials entrained by precipitated water from upper layers of soil to lower levels) that typically spans thousands of years, whereas a C horizon consists of slightly weathered parent material. The best approach to distinguishing a C horizon from an E horizon is to examine the morphology of the soil. For example, all E horizons have soil structure, which involves a bonding together of individual soil particles. In most E horizons, the particles are arranged about a horizontal plane, forming platy structure (Birkeland, 1999). In contrast, sandy C horizons are single grain or massive; hence, they lack soil structure. If the material is single grain, the individual sand particles are easily distinguishable and do not adhere to each other. When the material is massive, individual particles adhere closely to each other, but the mass lacks planes of weakness (Buol et al., 1997). Also, the boundary between an E and Bt horizon is usually gradual and wavy or irregular, and tongues of the E horizon often extend down into a Bt horizon. In contrast, where a C horizon overlies a truncated Bt horizon, the boundary is abrupt and smooth or wavy and lacks tongues.

Soils, unlike most individual beds of sediment, are laterally extensive across the landscape. They extend across various landforms and underlying geologic deposits and exhibit predictable variations in their properties related to changes in drainage, vegetation, and relative age of the geomorphic surface on which they occur. Hence, surface and buried soils can be mapped in three dimensions over varying topography. In contrast, individual beds of sediment tend to be restricted to a certain depositional environment and will pinch out away from that area.

Although identification and study of soils begins in the field with careful observations, it is sometimes necessary to support these observations with laboratory analysis in order to obtain a clear differentiation of soil from pedogenically unaltered sediment. One of the most powerful laboratory methods for distinguishing soil from nonsoil is micromorphological analysis (see Fisher and Macphail, 1985). This procedure, which requires the use of thin sections and petrographic equipment, greatly enhances the ability of the soil scientist to identify micropedological features that indicate pedogenic alteration (Brewer, 1976; Bullock et al., 1985; Douglas and Thompson, 1985; Courty et al., 1989). However, as Wilding and Flach (1985) have pointed out, soil micromorphology is a powerful tool to extend macromorphology and should not be used alone to distinguish soil from sediment. Because many soil properties form by the vertical movement and accumulation of some materials–such as clay, iron, and calcium carbonate–a wide variety of laboratory methods, such as grain-size and chemical analyses, can be helpful in differentiating soil from pedogenically unaltered sediment (Hesse, 1971; Soil Survey Staff, 1996; Buol et al., 1997).

Soils, Figure 4 A buried soil in the Arctic tundra of northern Canada. At the surface is late Holocene eolian sand with minimal soil development. The buried soil formed in glacial sand under boreal forest conditions. Scale in inches (Photo by James Knox).

Paleosols

The term *paleosol* is widely used in archaeology and other Quaternary studies and is variously defined. These definitions include soils of obvious antiquity (Morrison, 1967, 10), ancient soils (Butzer, 1971, 170), soils formed on a landscape of the past (Ruhe, 1965, 755; Yaalon, 1971a, 29; Gerrard, 1992, 202; Catt, 1998) or under an environment of the past (Yaalon, 1983; Schaetzl and Thompson, 2015), a soil with distinct evidence that the direction of soil development was different from that of the present (Catt, 1998), a soil formed during an earlier period of pedogenesis (Allaby and Allaby, 1991), or soils formed under conditions generally different from those of today (Plaisance and Cailleux, 1981, 702).

The study of paleosols is often referred to as *paleopedology* (Yaalon, 1971b; Retallack, 1990; Follmer, 1998). In a broad, holistic sense, the study of paleosols is a component of pedology, soil geomorphology, and soil stratigraphy. Pedology as traditionally taught in the USA and elsewhere does not deal with paleosols, and thus some workers have found it necessary to use the term *paleopedology*, essentially to differentiate a geoscientifically based study of soils from an agricultural one.

Specific types of paleosols include *buried soils*, which are soils covered by sediment (Figure 4), *relict soils*, which are soils formed on past landscapes or under past environments and never buried, and *exhumed soils*, which are soils that were buried and subsequently re-exposed (Ruhe, 1965; Valentine and Dalrymple, 1976) (see Johnson and Hole, 1994 for further discussion of these terms). Among these terms, "buried soil" is probably the least ambiguous, although a distinction between a "buried soil" and a "buried paleosol" has been proposed (Catt, 1998, 84). The former term is used for "soils buried by deposits too thin to seal them from present pedogenesis and not showing evidence of development in a direction different from the present" and the latter term proposed for soils that are buried and "isolated from present pedogenesis" and/or soils that are buried and exhibiting "distinct evidence that the direction of soil development was different from that of the present."

Otherwise, among the definitions and types of paleosols, exactly what constitutes a past landscape or past environment or how old the soil has to be was never defined. Because landscapes are always being subjected to some modification, and the environment is never static, and because all soils take some time to form, arguments have been made that all soils are paleosols and all unburied soils are relict soils, making such terms redundant (see also Bos and Sevink, 1975; Fenwick, 1985; Johnson et al., 1990; Johnson and Hole, 1994; Bronger and Catt 1998a; Bronger and Catt 1998b; Follmer, 1998; Johnson, 1998). Moreover, these definitions require that the history of the soil or the landscape or both be known before the term can be applied. The term "paleosol" seems to have some utility, however, judging from its widespread use (e.g., Follmer et al., 1998), especially in dealing with soils in the rock record, so-called pre-Quaternary soils (e.g., Retallack, 1990).

The terms *monogenetic* and *polygenetic* soils were based on geoarchaeological research (Bryan and Albritton, 1943). A "monogenetic soil" was initially defined as "one developed in one climatic regime" and a "polygenetic soil" as having "developed in more than one climatic regime" (Bryan and Albritton, 1943, Table on p. 477). Catt (1998, 84) provides more up-to-date definitions. A monogenetic soil "formed in a period when the variation in environmental factors was too small to produce detectably different assemblages of soil features . . . (i.e., the direction of soil development was constant)." A polygenetic soil "formed in two or more periods when the environmental factors were sufficiently different to produce detectably different assemblages of soil features. . . (i.e., the directions of soil development were different in the periods involved)." Similar to the criticism of the term and concept of paleosol (vs soil), some argue that there is no such thing as a monogenetic soil and that all soils are polygenetic because environmental factors are always changing to some degree (e.g., Working Group on the Origin and Nature of Paleosols, 1971, 155; Johnson et al., 1990; Johnson and Hole, 1994; Johnson, 1998). With the emphasis now placed on the direction of pedogenesis and the detectability of evidence for these changes, the terms may have merit and utility.

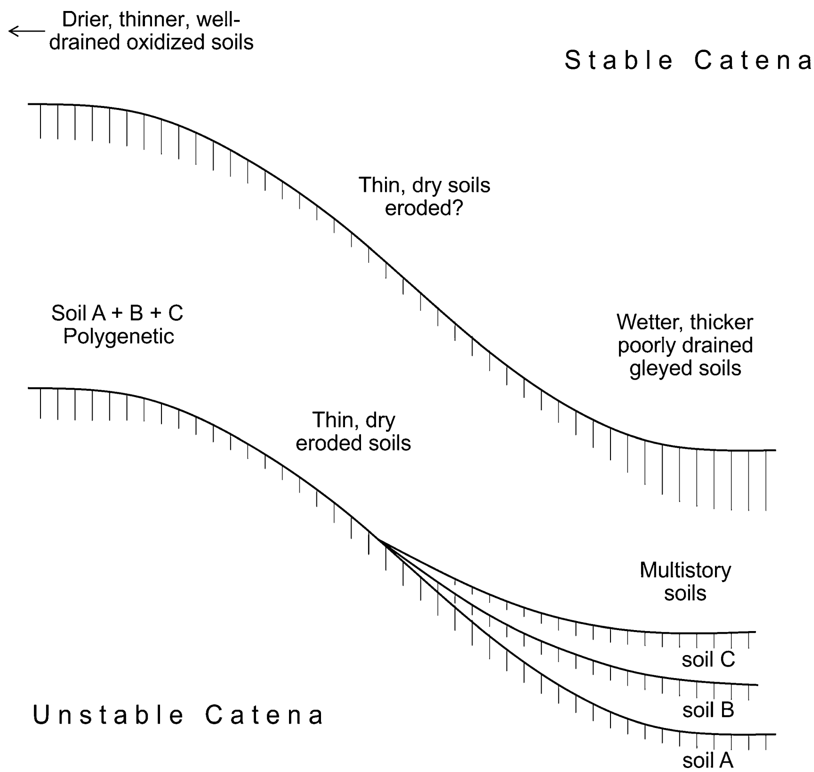
Recognition of buried soils, regardless of whether they are "paleosols," is especially important in archaeological surveys (see the entry on *Soil Stratigraphy* in this volume). Because buried soils represent previous land surfaces that were exposed for sufficient periods of time to develop recognizable soil profile characteristics, they also represent former stable land surfaces. If one assumes that the probability of cultural utilization of a particular landscape position is equal for each year, it follows that the surfaces that remain exposed for the longest time would represent those with the highest probability of containing cultural remains (Hoyer, 1980, 61). Because buried soils represent former stable surfaces, evidence for human occupation would more likely be associated with them (Mandel and Bettis, 2001). This reasoning also implies that a soil that had the most time to develop before it was buried would have the greatest likelihood of containing cultural deposits at any given location. Thus, buried soils are also useful indicators for locating archaeological deposits and for assessing an important aspect of the geologic potential for buried cultural deposits. A corollary to this is that the longer a given surface remains stable, the more likely it will have artifacts deposited on it. Cultural deposits within well-expressed soils therefore are more likely to represent palimpsest assemblages (remains from multiple occupations, most of which are compressed and possibly disturbed) than cultural deposits within weakly expressed soils that represent less elapsed time.

Knowledge of the temporal and spatial pattern of buried soils in a landscape provides archaeologists with a powerful tool for identifying areas with high potential for buried cultural deposits and for assessing prehistoric cultural records. There are many good examples of how this knowledge can be applied in an archaeological survey (e.g., Bettis and Benn, 1984; Mandel, 1985; May, 1986; Bettis and Littke, 1987; Mandel, 1988; Bettis, 1990; Mandel, 1992; Mandel, 1994a; Mandel, 1994b; Mandel, 1996; Mandel, 1999; Ferring, 2001; Mandel, 2002; Mandel, 2004; Mandel, 2006; Mandel, 2008; Mandel et al., 2009; Mandel, 2010; Mandel, 2013).

Catenas and soilscapes

The term *catena* describes a fundamental and significant aspect of soils. As originally proposed (Milne, 1935a; Milne, 1935b), a catena is a mapping unit defining a group or pattern of soils along a slope. In this definition, a catena forms as a result of differential drainage on the slope, with solutes leaching downslope and erosion and deposition occurring along the slope (Figure 5). In the USA, however, the term came to be applied to a sequence of soils developed in uniform parent material on a hillslope, with each soil varying according to drainage (Soil Survey Staff, 1951, 160). The term is often used interchangeably with *toposequence*–a group of soils that vary only in their topographic position but which otherwise formed in the same parent material, under the same climate and vegetation, and over the same amount of time (Jenny, 1980, 280; Hall, 1983, 124; Birkeland, 1999, 235; Schaetzl and Anderson, 2005, 469; Buol et al., 2011, 129–130). The processes of erosion and deposition inherent in the formation of catenas mean that the age of the landscapes will vary, however.

Related to catena is the concept of the *soilscape*. A soilscape is the pedologic portion of the landscape (Buol et al., 2011, 361) or the pattern and distribution of soils across the landscape. In a sense, soilscapes represent the expansion or distribution of catenas across the landscape. Catenary relationships among soils on a slope and the distribution of catenas across soilscapes are unique characteristics of soils, as they form on and across landscapes, and they serve to distinguish soils from other geologic phenomena.



Soils, Figure 5 Schematic illustrations of stable vs. unstable catenas (Modified from Holliday, 2004, Figure 9.1). If the slope is stable, a predictable sequence of soils will be found. If the slope is unstable, a sequence of buried soils will be found in the lower slope position.

Soil classification

Soil classification refers to the categorization of soils into groups at varying levels of generalization according to their morphological and chemical properties and sometimes their assumed genesis (Buol et al., 2011, 4). The purpose of classification is to (1) systematize knowledge about soils and (2) determine the processes that control similarity within a group and dissimilarities among groups (Birkeland, 1999, 29). The classification system used in the USA is the US Comprehensive Soil Classification System, published as the *Soil Taxonomy* (Soil Survey Staff, 1975; Soil Survey Staff, 1999; ftp://ftp-fc.sc.egov.usda.gov/NSSC/Soil_Taxonomy/tax.pdf) and updated in the *Keys to Soil Taxonomy*, ftp://ftp-fc.sc.egov.usda.gov/NSSC/Soil_Taxonomy/keys/2010_Keys_to_Soil_Taxonomy.pdf. Twelve soil orders are recognized in *Soil Taxonomy* (Table 3).

Soil Taxonomy was designed to facilitate classification for soil survey and land-use purposes (see the entry on Soil Survey in this volume) (Soil Survey Staff, 1975, 7–8; Bartelli, 1984). It was not intended to be a tool in soil-geomorphic or other geoscientific research. The system does not provide a means of understanding relationships between soils beyond their spatial relationships on soil maps. Of particular significance to geoarchaeology, *Soil Taxonomy* is not well suited for application to buried soils (see the entry on Soil Stratigraphy in this volume) and inadequately deals with soils heavily altered by human activity (*anthropogenic soils* or *anthrosols*; see the entry on Anthrosols in this volume).

Nevertheless, *Soil Taxonomy* forms the basis for much of the soils terminology in the USA and some of the international soil science terms. Becoming familiar with basic concepts and terms in soil classification will therefore facilitate geoarchaeological research. Basic introductions to *Soil Taxonomy* and some of the other systems are readily accessible (Birkeland, 1999; Holliday, 2004; Buol et al., 2011; Schaetzl and Thompson, 2015). Outside the USA, the most widely used system is the World Reference Base (WRB) for Soil Resources (IUSS, 2006).

Comparisons of the structure, philosophy, advantages, and disadvantages of a variety of soil classification systems, including *Soil Taxonomy*, are provided by Buol et al. (2011, 169–192). The International Institute for Geo-Information Science and Earth Observation (ITC) in the Netherlands has prepared a very useful "Compendium of On-Line Soil Survey Information," including information on, and comparisons among, the major national soil classification systems: www.itc.nl/~rossiter/research/rsrch_ss_class.html.

Soils, Table 3 General concepts of the soil orders in *Soil Taxonomy*[a]

Alfisols	Soils with an argillic horizon, but no mollic; they are lower in bases than Mollisols; typically found in humid, temperate regions
Andisols	Soils formed in volcanic ash and related volcanic parent materials
Aridisols	Soils formed in desert conditions (Entisols can also be found in deserts) or under other conditions restricting moisture availability to plants (high salt content; soils on slopes); some development in the B horizon, often evidenced by slight weathering or by illuvial compounds of calcium, gypsum, or other materials
Entisols	Soils with little evidence of pedogenesis; very few diagnostic horizons
Gelisols	Soils with permafrost within 2 m of the surface; very common in high latitudes
Histosols	Organic soils without permafrost, such as peats; dominated by decomposing organic matter
Inceptisols	Soils exhibiting more pedogenic development than Entisols with the appearance of diagnostic surface and subsurface horizons that are not as well developed as in most other orders
Mollisols	Soils with a thick, dark mollic epipedon that are high in bases throughout; typical of continental grasslands or savanna
Oxisols	Soils that are highly weathered and dominated by oxide, low-activity clays; they have an oxic (Bo) horizon; they are found in tropical regions and include many soils formerly termed Laterites and Latosols
Spodosols	Soils with spodic horizons; translocation and subsurface accumulation of compounds of humus and Al, and sometimes also Fe, have occurred; typical in cool, humid climates under coniferous forests
Ultisols	Highly weathered, acidic soils with argillic (Bt) horizons and very low in bases; typically found on older landscapes in warm, humid climates
Vertisols	Soils high in clay content in climates with distinct wet and dry seasons and that shrink and swell markedly; they develop deep cracks in the dry seasons; typically found in grasslands and savannas

[a]For a complete list with criteria see *Soil Taxonomy* (Soil Survey Staff, 1999). To classify a soil properly, one must follow the guidelines and criteria for diagnostic horizons and classification in *Soil Taxonomy* (Soil Survey Staff, 1999). This table presents only the principal characteristics of the soil orders.

Bibliography

Allaby, A., and Allaby, M. (eds.), 1991. *The Concise Oxford Dictionary of Earth Sciences*. New York: Oxford University Press.

Allen, J. R. L., 1986. Pedogenic calcretes in the Old Red Sandstone Facies (Late Silurian-Early Carboniferous) of the Anglo-Welsh area, Southern Britain. In Wright, V. P. (ed.), *Paleosols: Their Recognition and Interpretation*. Princeton, NJ: Princeton University Press, pp. 58–86.

Amundson, R., and Jenny, H., 1991. The place of humans in the state factor theory of ecosystems and their soils. *Soil Science*, **151**(1), 99–109.

Arakel, A. V., 1986. Evolution of calcrete in palaeodrainages of the Lake Napperby area, central Australia. *Palaeogeography Palaeoclimatology Palaeoecology*, **54**(1–4), 283–303.

Arrhenius, O., 1931. Die Bodenanalyse im Dienst der Archäologie. *Zeitschrift für Pflanzenernährung, Düngung, and Bodenkunde*, **10**(27–29), 427–439.

Arrhenius, O., 1963. Investigation of soil from old Indian sites. *Ethnos*, **28**(2–4), 122–136.

Bachman, G. O., and Machette, M. N., 1977. *Calcic Soils and Calcretes in the Southwestern United States*. USGS Open File Report 77-794. Reston, VA: US Geological Survey.

Bartelli, L. J., 1984. Soil taxonomy: its evolution, status, and future. In Grossman, R. B., Rust, R. H., and Eswaran, H. (eds.), *Soil Taxonomy: Achievements and Challenges*. Madison, WI: Soil Science Society of America. SSSA Special Publication 14, pp. 7–13.

Berlin, C. L., Ambler, J. R., Hevly, R. H., and Schaber, G. G., 1977. Identification of a Sinagua agricultural field by aerial thermography, soil chemistry, pollen/plant analysis, and archaeology. *American Antiquity*, **42**(4), 588–600.

Bettis, E. A., III, 1990. *Holocene Alluvial Stratigraphy and Selected Aspects of the Quaternary History of Western Iowa*. Iowa City, IA: University of Iowa. Iowa Quaternary Studies Group Contribution 36.

Bettis, E. A., III, and Benn, D. W., 1984. An archaeological and geomorphological survey in the Central Des Moines River Valley, Iowa. *Plains Anthropologist*, **29**(105), 211–227.

Bettis, E. A., III, and Littke, J. P., 1987. *Holocene Alluvial Stratigraphy and Landscape Development in Soap Creek Watershed, Appanoose, Davis, Monroe, and Wapello Counties, Iowa*. Open File Report 87-2. Iowa City: Iowa Department of Natural Resources, Geological Survey Bureau.

Bidwell, O. W., and Hole, F. D., 1965. Man as a factor of soil formation. *Soil Science*, **99**(1), 65–72.

Birkeland, P. W., 1999. *Soils and Geomorphology*, 3rd edn. New York: Oxford University Press.

Bos, R. H. G., and Sevink, J., 1975. Introduction of gradational and pedomorphic features in descriptions of soils: A discussion of the soil horizon concept with special reference to paleosols. *Journal of Soil Science*, **26**(3), 223–233.

Brewer, R., 1976. *Fabric and Mineral Analysis of Soils*. Huntington, NY: Robert E. Krieger, reprint with supplement.

Bronger, A., and Catt, J. A., 1998a. The position of paleopedology in geosciences and agricultural sciences. *Quaternary International*, **51–52**, 87–93.

Bronger, A., and Catt, J. A., 1998b. Summary outline and recommendations on paleopedological issues. *Quaternary International*, **51–52**, 5–6.

Bryan, K., and Albritton, C. C., Jr., 1943. Soil phenomena as evidence of climatic changes. *American Journal of Science*, **241**(8), 469–490.

Bullock, P., Fedoroff, N., Jongerius, A., Stoops, G., and Tursina, T., 1985. *Handbook for Soil Thin Section Description*. Wolverhampton, UK: Waine Research Publications.

Buol, S. W., Hole, F. D., and McCracken, R. J., 1989. *Soil Genesis and Classification*, 3rd edn. Ames, IA: Iowa State University Press.

Buol, S. W., Hole, F. D., McCracken, R. J., and Southard, R. J., 1997. *Soil Genesis and Classification*, 4th edn. Ames, IA: Iowa State University Press.

Buol, S. W., Southard, R. J., Graham, R. C., and McDaniel, P. A., 2011. *Soil Genesis and Classification*, 6th edn. Chichester, UK: Wiley-Blackwell.

Butzer, K. W., 1971. *Environment and Archaeology: An Ecological Approach to Prehistory*, 2nd edn. Chicago: Aldine.

Catt, J. A., 1986. *Soils and Quaternary Geology: A Handbook for Field Scientists*. Oxford: Clarendon.

Catt, J. A., 1998. Report from working group on definitions used in paleopedology. *Quaternary International*, **51–52**, 84.

Cornwall, I. W., 1958. *Soils for the Archaeologist*. London: Phoenix House.

Courty, M.-A., 1992. Soil micromorphology in archaeology. In Pollard, A. M. (ed.), *New Developments in Archaeological Science: A Joint Symposium of the Royal Society and the British Academy, February 1991*. Oxford: Oxford University Press, pp. 39–59.

Courty, M. A., Goldberg, P., and Macphail, R. I., 1989. *Soils and Micromorphology in Archaeology*. Cambridge: Cambridge University Press.

Daniels, R. B., and Hammer, R. D., 1992. *Soil Geomorphology*. New York: Wiley.

Douglas, L. A., and Thompson, M. L. (eds.), 1985. *Soil Micromorphology and Soil Classification, with Glossary Supplement*. Madison, WI: Soil Science Society of America. SSSA Special Publication 15.

Eidt, R. C., 1977. Detection and examination of anthrosols by phosphate analysis. *Science*, **197**(4311), 1327–1333.

Eidt, R. C., 1984. *Advances in Abandoned Settlement Analysis: Application to Prehistoric Anthrosols in Colombia, South America*. Milwaukee, WI: Center for Latin America, University of Wisconsin.

Eidt, R. C., 1985. Theoretical and practical considerations in the analysis of anthrosols. In Rapp, G. R., and Gifford, J. A. (eds.), *Archaeological Geology*. New Haven: Yale University Press, pp. 155–190.

Fenwick, I. M., 1985. Paleosols: problems of recognition and interpretation. In Boardman, J. (ed.), *Soils and Quaternary Landscape Evolution*. Chichester, UK: Wiley, pp. 3–21.

Ferring, C. R., 2001. Geoarchaeology in alluvial landscapes. In Goldberg, P., Holliday, V. T., and Ferring, C. R. (eds.), *Earth Sciences and Archaeology*. New York: Kluwer/Plenum Publishers, pp. 77–106.

Fisher, P. F., and Macphail, R. I., 1985. Studies of archaeological soils and deposits by micromorphological techniques. In Fieller, N. R. J., Gilbertson, D. D., and Ralph, N. G. A. (eds.), *Paleoenvironmental Investigations: Research Designs, Methods and Data Analysis*. Oxford: British Archaeological Reports. British Archaeological Reports, International Series, Vol. 258, pp. 93–125.

Follmer, L. R., 1998. Preface. *Quaternary International*, **51–52**, 1–3.

Follmer, L. R., Johnson, D. L., and Catt, J. A. (eds.), 1998. Revisitation of concepts in paleopedology. *Quaternary International*, **51**–**52**, 1–221.

Gerrard, J., 1992. *Soil Geomorphology: An Integration of Pedology and Geomorphology*. London: Chapman and Hall.

Gile, L. H., and Grossman, R. B., 1979. *The Desert Project Soil Monograph: Soils and Landscapes of a Desert Region astride the Rio Grande Valley near Las Cruces, New Mexico*. Washington, DC: US Department of Agriculture, Soil Conservation Service.

Gile, L. H., and Hawley, J. W., 1966. Periodic sedimentation and soil formation on an alluvial-fan piedmont in southern New Mexico. *Soil Science Society of America Proceedings*, **30**(2), 261–268.

Gile, L. H., Peterson, F. F., and Grossman, R. B., 1966. Morphological and genetic sequences of carbonate accumulation in desert soils. *Soil Science*, **101**(5), 347–360.

Hall, G. F., 1983. Pedology and geomorphology. In Wilding, L. P., Smeck, N. E., and Hall, G. F. (eds.), *Pedogenesis and Soil Taxonomy: Part 1, Concepts and Interactions*. Amsterdam: Elsevier. Developments in Soil Science 11A, pp. 117–140.

Hesse, P. R., 1971. *A Textbook of Soil Chemical Analysis*. New York: Chemical Publishing.

Holliday, V. T., 1990. Pedology in archaeology. In Lasca, N. P., and Donahue, J. (eds.), *Archaeological Geology of North America*. Boulder, CO: Geological Society of America. GSA Centennial Volume, Vol. 4, pp. 525–540.

Holliday, V. T., 1992. Soil formation, time, and archaeology. In Holliday, V. T. (ed.), *Soils in Archaeology: Landscape Evolution and Human Occupation*. Washington, DC: Smithsonian Institution Press, pp. 101–117.

Holliday, V. T., 2004. *Soils in Archaeological Research*. Oxford: Oxford University Press.

Hoyer, B. E., 1980. The geology of the Cherokee Sewer site. In Anderson, D. C., and Semken, H. A., Jr. (eds.), *The Cherokee Excavations: Holocene Ecology and Human Adaptations in Northwestern Iowa*. New York: Academic, pp. 21–66.

IUSS, 2006. *World Reference Base for Soil Resources, 2006: A Framework for International Classification, Correlation and Communication*, 2nd edn. Rome: FAO. International Union of Soil Scientists Working Group and World Soil Resources Report 103.

Jacobsen, G., Arakel, A. V., and Yijian, C., 1988. The central Australian groundwater discharge zone: evolution of associated calcrete and gypcrete deposits. *Australian Journal of Earth Sciences*, **35**(4), 549–565.

Jenny, H., 1941. *Factors of Soil Formation: A System of Quantitative Pedology*. New York: McGraw-Hill.

Jenny, H., 1980. *The Soil Resource: Origin and Behavior*. New York: Springer.

Johnson, D. L., 1998. Paleosols are buried soils. *Quaternary International*, **51–52**, 7.

Johnson, D. L., and Hole, F. D., 1994. Soil formation theory: A summary of its principal impacts on geography, geomorphology, soil-geomorphology, Quaternary geology, and paleopedology. In Amundson, R. (ed.), *Factors of Soil Formation: A Fiftieth Anniversary Retrospective*. Madison, WI: Soil Science Society of America. SSSA Special Publication 33, pp. 111–126.

Johnson, D. L., and Watson-Stegner, D., 1990. The soil evolution model as a framework for evaluating pedoturbation in archaeological site formation. In Lasca, N. P., and Donahue, J. (eds.), *Archaeological Geology of North America*. Boulder, CO: Geological Society of America. GSA Centennial Special Volume, Vol. 4, pp. 541–560.

Johnson, D. L., Keller, E. A., and Rockwell, T. K., 1990. Dynamic pedogenesis: New views on some key soil concepts, and a model for interpreting Quaternary soils. *Quaternary Research*, **33**(3), 306–319.

Machette, M. N., 1985. Calcic soils of the Southwestern United States. In Weide, D. L. (ed.), *Soils and Quaternary Geology of the Southwestern United States*. Boulder, CO: Geological Society of America. GSA Special Paper 203, pp. 1–22.

Mandel, R. D., 1985. Geomorphological investigation of the Cedar Cross Corridor. In Overstreet, D. F. (ed.), *Phase II Intensive Cultural Resources Survey of the Cedar Cross Corridor, Dubuque County, Iowa*. Waterloo, IA: Brice, Petrides and Donahue, pp. 36–38.

Mandel, R. D., 1988. Geomorphology of the Pawnee River Valley. In Timberlake, R. D. (ed.), *Phase II Archaeological and Geomorphological Survey of the Proposed Pawnee River Watershed, Covering Subwatersheds 3 through 7, Ness, Fort, Lane, and Finney Counties, Southwest Kansas*. Topeka, KS: Kansas Historical Society, pp. 68–115.

Mandel, R. D., 1992. Soils and Holocene landscape evolution in central and southwestern Kansas: implications for

archaeological research. In Holliday, V. T. (ed.), *Soils and Landscape Evolution*. Washington, DC: Smithsonian Institution Press, pp. 41–100.
Mandel, R. D., 1994a. Geomorphology and stratigraphy of Lower Mill Creek Valley, Johnson County, Kansas. In Gillen, T. V., Winham, R. P., Lueck, E. J., and Hanus, L. A. (eds.), *Archeological Test Excavations at Six Prehistoric Sites within the Lower Mill Creek Valley, Johnson County, Kansas*. Sioux Falls, SD: Archeology Laboratory, Augustana College. Archeology Contract Series, Vol. 99, pp. 96–125.
Mandel, R. D., 1994b. Holocene landscape evolution in the Big and Little Blue River valleys, eastern Nebraska: Implications for archaeological research. In Lueck, E. J., and Winham, R. P. (eds.), *Blue River Drainage Intensive Archaeological Survey, 1992–1993, Seward and Thayer Counties, Nebraska*. Sioux Falls, SD: Archeology Laboratory, Augustana College. Archeology Contract Series, Vol. 84, pp. H-1–H-79.
Mandel, R. D., 1996. Geomorphology of the South Fork Big Nemaha River valley, southeastern Nebraska. In Holen, S. R., Peterson, J. K., and Watson, D. R. (eds.), *A Geoarchaeological Survey of the South Fork Big Nemaha Drainage, Pawnee and Richardson Counties, Nebraska*. Nebraska Archaeological Survey, Technical Report 95-02, Lincoln, Nebraska, University of Nebraska State Museum, pp. 26–81.
Mandel, R. D., 1999. *Geomorphology and Late Quaternary Stratigraphy of the Big Blue River and Lower Beaver Creek Valleys, Southeastern Nebraska, volume 1: Archeological Investigations of the Lower Beaver Creek and Big Blue River Drainages in Furnas, Red Willow, Pawnee, and Gage Counties, Nebraska: 1997–1998.* Archeology Contract Series No. 137, Sioux Falls, SD: Archeology Laboratory, Augustana College.
Mandel, R. D., 2002. Geomorphological investigation. In Pepperl, R. E. (ed.), *Archaeological Investigations in the Elkhorn-Platte River Confluence Area, Western Douglas and Sarpy Counties, Nebraska*. Lincoln, NE: Nebraska State Historical Society Archaeological Survey Report. Cultural Resources Planning Studies for the Lower Platte River Basin Area No. 2, pp. A-1–A-91.
Mandel, R. D., 2004. Geomorphological investigations. In Raab, H. A., Boden, P. J., and Rust, J. R. (eds.), *Cultural Resources Inventory for a Flood Control Project, Augusta, Kansas*. St. Paul, MN: Report prepared by 4G Consulting, LLC and submitted to the US Army Corps of Engineers, pp. 7-1–7-34.
Mandel, R. D., 2006. *Geomorphology, Quaternary Stratigraphy, and Geoarchaeology of Fox Creek Valley, Tallgrass Prairie National Preserve, Northeast Kansas*. Lawrence, KS: Kansas Geological Survey Open-File Report, pp. 2006–2029.
Mandel, R. D., 2008. Geomorphological investigation. In Bozell, J. R., Buhta, A. A., Mandel, R. D., Holen, S. R., and E. J. Lueck, E. J. (prep.), *An Archeological and Geomorphic Survey of Select Lands in the Broadwater West and Blue Creek Study Areas, Morrill and Garden Counties, Nebraska*. Archeological Contract Series No. 226. Sioux Falls, SD: Archeology Laboratory, Augustana College, pp. 210–224.
Mandel, R. D., 2010. Geoarchaeological investigation. In Kruse, J. J., Buhta, A. A., and Mandel, R. D. (prep.), *An Archaeological and Geomorphological Survey of Select Lands along the Platte River Bluffs and along Silver and Wahoo Creeks, Saunders County, Nebraska*. Archaeological Contract Series No. 240. Sioux Falls, SD: Archeology Laboratory, Augustana College, pp. 140–162.
Mandel, R. D., 2013. Geomorphological investigation. In Palmer, L., Buhta, A. A., Kruse, J. M., and Mandel, R. D. (prep.), *An Archeological and Geomorphological Survey of Select Lands Along Oak Creek and Salt Creek in the Vicinity of Lincoln, Lancaster County, Nebraska*. Archeological Contract Series No. 260. Sioux Falls, South Dakota: Archeology Laboratory, Augustana College, pp. 90–128.
Mandel, R. D., and Bettis, E. A., III, 2001. Use and analysis of soils by archaeologists and geoscientists: a North American perspective. In Goldberg, P., Holliday, V. T., and Ferring, C. R. (eds.), *Earth Sciences and Archaeology*. New York: Kluwer/Plenum Publishers, pp. 173–204.
Mandel, R. D., Saunders, J. W., Hall, G. D., and McCulloch, S., 2009. Geomorphological and archaeological assessment. In Carlson, D. L., Clabaugh, P. A., Mandel, R. D., and Pevy, C. D. (eds.), *Prehistoric Archaeological Investigations in the Applewhite Reservoir Project Area, Bexar County, Texas*. Reports of Investigations 7. College Station, TX: Center for Ecological Archaeology, Texas A&M University, pp. 127–165.
Mann, A. W., and Horowitz, R. D., 1979. Groundwater calcrete deposits in Australia: some observations from western Australia. *Australian Journal of Earth Sciences*, **26**(5), 293–303.
May, D. W., 1986. Geomorphology. In Blakeslee, D. J., Blasing, R. K., and Garcia, H. F. (eds.), *Along the Pawnee Trail: Cultural Resource Survey and Testing at Wilson Lake, Kansas*. Kansas City, MO: U.S. Army Corps of Engineers, pp. 72–86.
Milne, G., 1935a. Composite units for the mapping of complex soil associations. *Transactions of the Third International Congress of Soil Science, Oxford, England*, **1**, pp. 345–347. London: T. Murby.
Milne, G., 1935b. Some suggested units for classification and mapping, particularly for East African soils. *Soil Research*, **4**, 183–198.
Minasny, B., McBratney, A. B., and Salvador-Blanes, S., 2008. Quantitative models for pedogenesis–a review. *Geoderma*, **144** (1–2), 140–157.
Morrison, R. B., 1967. Principles of Quaternary soil stratigraphy. In Morrison, R. B., and Wright, H. E., Jr. (eds.), *Quaternary Soils*. Reno, NV: University of Nevada Desert Research Institute, Center for Water Resources Research, pp. 1–69.
Nikiforoff, C. C., 1949. Weathering and soil evolution. *Soil Science*, **67**(3), 219–230.
Paton, T. R., Humphreys, G. S., and Mitchell, P. B., 1995. *Soils: A New Global View*. New Haven: Yale University Press.
Plaisance, G., and Cailleux, A., 1981. *Dictionary of Soils*. New Delhi: Amerind Publishing.
Retallack, G. J., 1990. *Soils of the Past: An Introduction to Paleopedology*. Boston: Unwin and Hyman.
Ruhe, R. V., 1956. Geomorphic surfaces and the nature of soils. *Soil Science*, **82**(6), 441–456.
Ruhe, R. V., 1965. Quaternary paleopedology. In Wright, H. E., and Frey, D. G. (eds.), *The Quaternary of the United States*. Princeton, NJ: Princeton University Press, pp. 755–764.
Schaetzl, R. J., and Anderson, S., 2005. *Soils: Genesis and Geomorphology*. New York: Cambridge University Press.
Schaetzl, R. J., and Thompson, M. L., 2015. *Soils: Genesis and Geomorphology*, 2nd edn. New York: Cambridge University Press.
Schelling, J., 1970. Soil genesis, soil classification and soil survey. *Geoderma*, **4**(3), 165–193.
Schoeneberger, P. J., Wysocki, D. A., Benham, E. C., and Broderson, W. D. (eds.), 2002. *Field Book for Describing and Sampling Soils*, Version 2.0. Lincoln, NE: National Soil Survey Center, National Resources Conservation Service, U.S. Department of Agriculture.
Simonson, R. W., 1959. Outline of a generalized theory of soil genesis. *Soil Science Society of America Proceedings*, **23**(2), 152–156.
Simonson, R. W., 1978. Multiple process model of soil genesis. In Mahaney, W. C. (ed.), *Quaternary Soils*. Norwich, UK: Geo Abstracts, pp. 1–25.

Smeck, N. E., Runge, E. C. A., and Mackintosh, E. E., 1983. Dynamics and genetic modeling of soil systems. In Wilding, L. P., Smeck, N. E., and Hall, G. F. (eds.), *Pedogenesis and Soil Taxonomy: Part 1, Concepts and Interactions*. Amsterdam: Elsevier. Developments in Soil Science 11A, pp. 51–81.
Soil Science Society of America, 2008. *Glossary of Soil Science Terms 2008*. Madison, WI: Soil Science Society of America.
Soil Survey Division Staff, 1993. *Soil Survey Manual*, revised. USDA Handbook 18. Washington, DC: US Department of Agriculture.
Soil Survey Staff, 1951. *Soil Survey Manual*. Washington, DC: Agricultural Research Administration, US Department of Agriculture. USDA Handbook 18.
Soil Survey Staff, 1975. *Soil Taxonomy: A Basic System of Soil Classification for Making and Interpreting Soil Surveys*. Washington, DC: Soil Conservation Service, US Department of Agriculture. Agriculture Handbook 436.
Soil Survey Staff, 1996. *Keys to Soil Taxonomy*, 7th edn. Washington, DC: US Department of Agriculture, Natural Resources Conservation Service.
Soil Survey Staff, 1999. *Soil Taxonomy*, 2nd edn. Washington, DC: US Department of Agriculture. Agriculture Handbook 436.
Solecki, R. S., 1951. Notes on soil analysis and archaeology. *American Antiquity*, **16**(3), 254–256.
Tandarich, J. P., and Sprecher, S. W., 1994. The intellectual background for the factors of soil formation. In Amundson, R. R., Harden, J., and Singer, M. (eds.), *Factors of Soil Formation: A Fiftieth Anniversary Retrospective*. Madison, WI: Soil Science Society of America. SSSA Special Publication 33, pp. 1–13.
Valentine, K. W. G., and Dalrymple, J. B., 1976. Quaternary buried paleosols: a critical review. *Quaternary Research*, **6**(2), 209–222.
Wilding, L. P., and Flach, K. W., 1985. Micropedology and soil taxonomy. In Douglas, L. A., and Thompson, M. L. (eds.), *Soil Micromorphology and Soil Classification*. Madison, WI: Soil Science Society of America. SSSA Special Publication 15, pp. 1–16.
Working Group on the Origin and Nature of Paleosols, 1971. Criteria for the recognition and classification of paleosols. In Yaalon, D. H. (ed.), *Paleopedology: Origin, Nature and Dating of Paleosols*. Jerusalem: International Society of Soil Science and Israel Universities Press, pp. 153–158.
Wright, V. P., 1982. Calcrete palaeosols from the Lower Carboniferous Llanelly Formation, South Wales. *Sedimentary Geology*, **33**(1), 1–33.
Yaalon, D. H., 1971a. Soil-forming processes in time and space. In Yaalon, D. H. (ed.), *Paleopedology: Origin, Nature and Dating of Paleosols*. Jerusalem: International Society of Soil Science and Israel Universities Press, pp. 29–39.
Yaalon, D. H. (ed.), 1971b. *Paleopedology: Origin, Nature and Dating of Paleosols*. Jerusalem: International Society of Soil Science and Israel Universities Press.
Yaalon, D. H., 1983. Climate, time and soil development. In Wilding, L. P., Smeck, N. E., and Hall, G. F. (eds.), *Pedogenesis and Soil Taxonomy: Part 1, Concepts and Interactions*. Amsterdam: Elsevier. Developments in Soil Science 11A, pp. 233–251.

Cross-references

Anthrosols
Microstratigraphy
Site Formation Processes
Soil Geomorphology
Soil Micromorphology
Soil Stratigraphy
Soil Survey
Soils, Agricultural

SOILS, AGRICULTURAL

Jonathan A. Sandor[1] and Jeffrey A. Homburg[2]
[1]Agronomy Department, Iowa State University, Corrales, NM, USA
[2]Statistical Research, Inc, Tucson, AZ, USA

Introduction

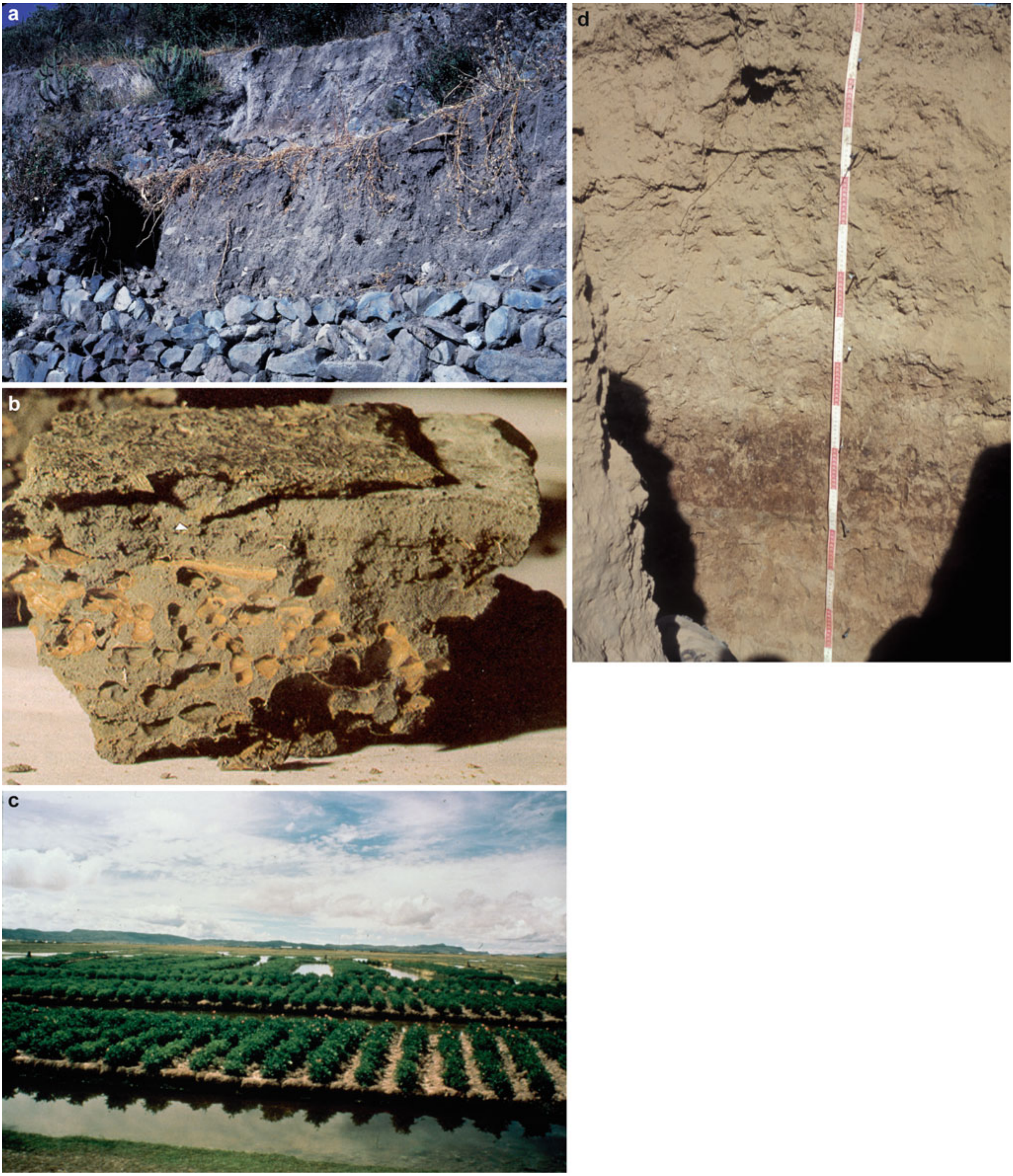
The geoarchaeological record holds key information about past land use and its impact on soils and environment. Among agents of anthropogenic soil change, agriculture's impact on soil is immense in magnitude, spatial extent, and duration. Agriculture has profoundly altered soil properties, processes, and formation pathways worldwide since its inception about ten millennia ago. The deep time perspectives on soil management and change available through geoarchaeology can help us predict long-term effects of agriculture on land resources and test for sustainability. Ancient agricultural systems and soils presented here illustrate the global range of soil use and change in relation to complex, interacting factors such as kind of system, time scale, and environmental setting and resilience.

Kinds of ancient agricultural systems and soils

Certain kinds of anthropogenic soils are associated with agricultural systems that have functioned for centuries to millennia. Some of these soils have been altered to a limited extent from their original form, or buried to varying depths, while others have been transformed into truly anthropogenic soils. Major forms of anthropogenic soils include plaggen soils, Amazonian Dark Earth soils (ADE or terra preta), terraced soils, paddy and other wet-field soils, and irragric soils (Figure 1, Table 1). Although each has a distinct combination of properties, a wide range exists within them as well as some degree of overlap among them due to similar soil-forming processes or equifinality. For example, the upper horizons of plaggen, ADE, terraced, and irragric soils are thickened from deliberate to inadvertent additions of organic matter and sediment. Because water deficiency or excess is of major concern in most agricultural systems, many soils have been altered by water management practices such as irrigation or drainage. Plaggen soils and ADE soils are discussed in greater depth in another article (see Woods and Macphail), so this one emphasizes the latter three kinds along with some comparisons related to soil change.

Terraced soils

Terracing constitutes some of humanity's most enduring efforts to manage soil, water, and geomorphic processes in agriculture and to protect land resources. The stepped topography created by terracing is a characteristic feature of sloping lands on five continents and Oceania. Most of the earliest documented ages for terracing in a number of world regions are similar at roughly 3,000–4,000 year



Soils, Agricultural, Figure 1 (**a**) Ancient terraced soil with thickened surface horizons, Colca Valley, Peru. (**b**) Paddy soil sample. Variegated colors from flooding and alternating reduction/oxidation. Vesicles formed from gases trapped beneath puddled surface soil (Source: Moorman and van Breemen 1978). (**c**) Reconstructed raised fields near Lake Titicaca in Peru (Photo by Clark Erickson). (**d**) Ancient irragric soil, Gila River Indian Community, Arizona. Light-colored irrigation sediment buries natural horizon of clay accumulation. Irrigation in this area spans about 450–1450 AD. Scale band divisions are 10 cm.

Soils, Agricultural, Table 1 Major kinds of ancient agricultural soils

Soil	Oldest age/main age (year BP)	Geographic location (major)	Main features/processes
Plaggen	3000/Middle ages	Northern Europe	Thick, organic matter- and phosphorus-rich surface horizon from long-term additions of manure and other materials. Commonly contains artifacts
Terra preta (Amazonian Dark Earth)	2500/1000	Amazonia	Dark soil from charcoal and additions of other organic materials. Artifacts such as pottery sherds common
Terraced soils	6000/1000–4000	5 continents and Oceania	Thickened A horizons from construction and/or sedimentation upslope of terrace walls
Paddy soils	6000/2000	Southeastern Asia	Anthraquic, redoximorphic features (from reduction and oxidation of iron and manganese), puddled surface, and other properties resulting from wet rice production
Raised field soils	2000–3000/1000	Central and S. America	Soil buildup in ridges on wetlands. Organic and other materials from adjacent drainage ditches added to ridges
Irragric soils	5000 3000 3500 4000	Middle East Central Asia South America North America SW	Sediment accumulation from long-term irrigation. Variable salinity, organic matter, and other properties. Artifacts such as pottery sherds common

BP. Older ages from 6,000 year BP to possibly earlier have been reported.

Besides creating a stable topographic base for crops, functions of terracing include soil retention and erosion control, soil building by construction filling or sedimentation, microclimatic modification, and water control ranging from runoff management to irrigation, ponding, and drainage. In several arid regions, ancient terracing involved relatively subtle landscape alteration in the form of small dam construction to facilitate runoff agriculture. Lynchets, likely created incidentally from cultivation and associated erosion processes in northern Europe, also represent subtle terraced lands. In other regions terracing evolved into such remarkably engineered systems as bench terraces of the Andes and rice terraces of eastern Asia, where entire landscapes were transformed into stepped agroecosystems. Variability in the scale and durability of terrace structures means that some survive in the archaeological record while others have long since disappeared. Archaeological excavation of some terraced systems reveals multiple buried walls and other features that indicate complex histories or incremental construction.

Terraced soils have a wide range of physical, chemical, and biological properties (Sandor, 2006). One of the most distinctive morphological features is increased soil thickness resulting from accumulation of sediment upslope of terrace walls. Thickening within each terrace varies because of the wedge-shaped geometry common in terraced soil fills, wherein fills are thickest nearest the terraced wall and decrease upslope. At the lower end of the range, soils thicken slightly (few centimeters to decimeters) in the case of many runoff terraces on hillslopes and lynchets involving low terrace walls and accumulation by natural sedimentation. Substantial thickening from 0.3 up to several meters is common in bench terrace systems, wet-field terraces, and runoff terraces located in ephemeral drainages. The several traditional methods for filling terraces with soil or sediment by direct construction (versus natural sedimentation processes) greatly influence subsequent soil properties. In mountain terracing, construction filling with material originating on local slopes is common. Soil thickening is often a deliberate practice to create arable land on steep slopes that otherwise lack sufficient soil, or to increase soil rooting volume for water and nutrients. Buried horizons are characteristic of terraced soils where filling has occurred without destruction of the original soil. Where terrace filling is episodic or incremental, or where erosion has occurred, multiple fills and buried soil horizons may develop. Cases of such complex soils and strata in agricultural terraces have been studied in Greece, France, Mexico, Peru, and other locations (e.g., Krahtopoulou and Frederick, 2008; Bal et al., 2010).

Changes in soil texture are common, especially in upper horizons directly changed by construction filling and mixing of soil materials. Artificial gravel layers were placed at the fronts of some Andean terraces to aid drainage and reduce stress on terrace walls. Other textural changes reported in terraced fills ranging from subtle to substantial may result from sediment additions in irrigation water or runoff, or from downward translocation of fine particles, such as in agric horizons of lynchets (Courty et al., 1989). In Ifugao wet-field terraces in the Philippines, a sequence of textures is emplaced through deliberate water erosion upslope and then filling behind terrace walls downslope with coarser sediments first, followed by capping with fine sediments to achieve water ponding. Modification of soil structure and pores by terracing has also been documented.

Changes in several chemical soil properties have been measured in terraced soils, both in soil fills and deeper subsurface horizons. In soil fills, decreases and increases in organic carbon, nitrogen, phosphorus, some micronutrients, pH, carbonate, and cation exchange capacity have been found. Processes inducing increases in nutrients are additions in irrigation or runoff as well as fertilization. Decreases in soil nutrients result from crop removal as well as leaching and erosion processes. Some cases of subsurface chemical change result from translocation of dissolved or colloidal materials and the effects of burial by overlying terrace soil fills. An example is the movement of substantial phosphorus from manure applied as fertilizer in ancient Andean terraces deep into natural subsurface horizons (Sandor and Eash, 1995). Organic chemical compounds that are biomarkers of manure fertilizer have been detected in ancient Minoan terraced soils (Bull et al., 2001).

Under long-term transformation, many ancient terraced soils have acquired properties of anthropedogenic horizons defined in soil taxonomic systems such as the World Reference Base for Soil Resources, US Soil Taxonomy, and Chinese Soil Classification. Examples are plaggen, anthropic, anthraquic, and agric horizons that are recognized in several agricultural and archaeological contexts. Amendments, cultural debris, and other artifacts as well as high phosphorus levels have been identified in ancient terraced soils.

Paddy and other wet-field soils

Paddy soils are anthropogenic soils created for wet rice production (Zhang and Gong, 2003). They are most extensive in Southeast Asia, where fields more than 6,000 years old have been found (Cao et al., 2006). The goal in making paddy soils is to build bordered fields and soils with a sealed subsurface that ponds water during the first phase of the rice growing cycle, followed by field drainage to allow the rice crop to mature. The artificially created anthraquic soil hydrology, involving alternating ponding and draining through the rice growing cycle, results in anaerobic/aerobic biological activity and reduction/oxidation processes that alter soil organic and inorganic chemistry and impart the distinctive characteristics of paddy soils. Some of the main soil properties are puddled surface horizons and redoximorphic features such as reduced or gleyed matrix and redox depletions and concentrations of iron and manganese. Many paddy soils have a base-poor, bleached upper profile in which clay has been destroyed by ferrolysis, a process in which alternating reduction and oxidation from the periodic water ponding leads to soil acidification and albic E horizon formation.

Other ancient wet-field anthropogenic soils occur in various forms of raised fields, which are extensive in Central and South America, where they are as old as about 2,000–3,000 years (Beach et al. 2009). Many of these consist of soil ridges constructed and fertilized by additions of sediments and other materials to keep crops above shallow water tables. These were especially prevalent among the Maya and also occur in Mexico, the Andean Altiplano, and in Amazonia. In an example of "practical archaeology," a raised field system was reconstructed and successfully farmed in wetlands around Lake Titicaca in Peru (Erickson, 2000; Figure 1c).

Irragric soils

Irragric soils have been highly altered by long-term irrigation, especially from long-term deposition of suspended sediment by irrigation water (IUSS Working Group, 2006; Hesse and Baade, 2009). They were first characterized and are most prevalent in arid to semiarid central Asia and Mesopotamia, but are also found in other arid regions with long-term irrigation in southern Asia (India and Pakistan), the North America Southwest, and the western coastal area of Peru. Oldest ages are about 5,000 years in Mesopotamia, 3,000 years in Central Asia, 3,500 years in Peru, and 4,000 years in the North American Southwest. Irragric soil properties vary widely by region depending on the duration of irrigation, management practices, and irrigation water sediment load and chemistry. Common characteristics are thick, relatively homogeneous fine-textured horizons from irrigation sediment. Irragric soils may have higher organic matter levels, well-developed structure, lower to higher salt content than the original soils, and archaeological artifacts (Kostyuchenko and Lisitsyna, 1976).

Evaluating change in ancient agricultural soils

How have ancient agricultural soils changed from their original form, and by what processes? To answer these questions, we need to learn about the magnitude, spatial extent, and duration of soil change across a range of environmental and agricultural contexts (Sandor et al., 2005). Agriculture can alter soils both directly and indirectly by changing both soil morphology and underlying soil-forming processes and geomorphic, hydrologic, and ecosystem configuration. Some changes are intentional management strategies to increase soil productivity, such as soil chemical alteration by fertilization to increase nutrient content and availability. Other changes are unintended ones that lead to degradation such as soil erosion. Agriculture mainly changes surface horizons, though deeper alterations may occur. Some changes are subtle and temporary, while others are far reaching and permanent.

Long-term changes in soils from ancient agriculture have been inferred at landscape to submicroscopic scales using a number of field and laboratory approaches (Holliday, 2004). Methods to detect and measure soil change need to be carefully considered because they underpin all data and interpretation. Recognizing, measuring, and interpreting soil change from ancient agriculture can be difficult for several reasons: the sheer complexity of soils and their interaction with agroecosystems as well as post-agriculture soil change through continued soil development, environmental change, and later land use. In addition to this are the methodological challenges and relatively limited research. While soils in more intensive agricultural systems bear clear marks of change, other ancient agricultural soils can be very subtle. Patterns of soil change emerge, but each case produces its own distinct set of features, so there are no universal criteria. Soil change has been well documented in some areas, but in other areas, ancient agricultural soils remain unrecognized or insufficiently characterized.

Inferring soil change is primarily based on a "space-for-time substitution" method in which ancient cultivated soils are compared with nearby uncultivated reference soils in similar geomorphic and pedogenic settings (Homburg and Sandor, 2011). Because soils are dynamic, reference soils do not represent the original soils, but rather what cultivated soils would be like now had they not been farmed. Most comparative studies involve soils farmed during one discrete or undifferentiated past period. However, there are a few examples of anthrochronosequences in which soils farmed at multiple discrete periods have been identified, so paths of anthropogenic soil change can be traced. Another possible way to detect soil change is to identify dramatic or unique characteristics associated with some agricultural soils whose anthropogenic properties are far beyond the range found in natural soils, such as extraordinarily high phosphorus levels (e.g., Sandor and Eash, 1995).

Soil changes detected in ancient fields can be interpreted as a gradient from degradation to enhancement in the context of agricultural productivity and land resource conservation. Specific kinds of enhancement are A horizon thickening, structural stabilization, increased available water capacity, and gains of organic matter and nutrients. Examples of enhancement discussed in the previous section or elsewhere are the ADE soils, plaggen soils, and some terraced soils. Main forms of soil degradation inferred at ancient agricultural sites are accelerated erosion, structural deterioration, compaction, declines in organic matter and macronutrients such as nitrogen and phosphorus, salt and/or sodium accumulation, and acidification. In other cases, soil change may be indeterminate or intermediate between degradation and enhancement. Inconclusive findings may be due to methodological constraints like absence of reference soils for clear comparisons or insufficient sampling relative to soil variability and scale. Intermediate soil change could result from no net soil change, insignificant change, offsetting, mixed, inconclusive or contradictory change, or soil recovery from degradation or reversion from enhancement. Paddy soils reflect both enhancement and degradation, a kind of "creative destruction" (Johnson and Lewis, 1995). They involve destruction of surface horizon structure and properties resulting from anaerobic conditions, but this is deliberately managed to create the hydrologic conditions suitable for wet rice production.

Soil degradation has plagued agriculture throughout its 10+ millennia history. It has long-lasting consequences that can compromise societies' ability to function (Diamond, 2005). There is justified concern today about soil degradation and its adverse impacts on agricultural productivity and environmental quality. Some examples of soil degradation are presented next.

Accelerated erosion and sedimentation

Erosion resulting from agriculture and other human land use is referred to as "accelerated" because it usually occurs at higher rates than natural erosion; an order of higher magnitude is typical (Montgomery, 2007). Accelerated water erosion as sheet or gully erosion is most widespread, though there are also many instances of wind erosion (e.g., the Dust Bowl) and mass movement. A key reason for increased soil erosion is the loss of protective vegetation cover as natural ecosystems such as forests and grasslands are converted to farmland.

Surface horizons, which generally contain the most plant nutrients and organic matter, are the most immediately vulnerable to erosion. Especially subject to major change are those soils with well-developed, organic matter-rich surface horizons such as Mollisols. Such changes can persist for long time periods, even centuries after abandonment. As surfaces erode more deeply, subsurface horizons become shallower or exposed. If subsurface horizons inhibit plant growth, such as with salt-affected horizons, dense (e.g., claypans, fragipans) or cemented horizons (e.g., petrocalcic horizons, duripans), soil quality is further compromised.

Archaeological, stratigraphic, geomorphic, and pedologic (including micromorphology) studies of ancient agricultural soils have reconstructed complex histories of accelerated erosion in several regions, especially in the Mediterranean area, Europe, Mexico, and the Maya area (e.g., several chapters in Bell and Boardman, 1992; Houben, 2008; Krahtopoulou and Frederick, 2008; Beach et al., 2009). Several cases involve agricultural terraces, both as a response to erosion and as a cause if not maintained.

The counterpart to accelerated erosion is excessive sedimentation downslope, and many studies rely on sedimentation to infer erosion caused by ancient agriculture. The effect of sedimentation on soil productivity is a two-edged sword in that some sediment renews fertility, but excessive deposition is detrimental, burying crops and soils and causing off-site damage.

Organic matter and nutrient loss

Losses of soil organic matter and nutrients, resulting in soil fertility decline, have been most prevalent in semiarid to humid regions. Major causes are organic matter oxidation associated with tillage and cultivation, crop removal of nutrients that exceeds inputs, and clearing of native vegetation. Cases going back 5,000 years in Europe and 1,000 years in the Americas have been documented. Significant decline of soil organic matter, nitrogen, and phosphorus has persisted about nine centuries after the abandonment of some prehistoric fields in New Mexico, in amounts comparable to those in modern cultivated soils in the Midwest USA (Homburg and Sandor, 2011). Losses of soil nutrients, including phosphorus, calcium, magnesium, and potassium, were measured in ancient Hawaiian fields (Hartshorn et al., 2006).

Compaction and structural degradation

Compaction refers to increase in soil bulk density over the natural condition. In agriculture, compaction is usually an inadvertent and undesirable outcome of tillage and cultivation, involving decrease in overall porosity and especially macropores (pores generally >0.075 mm in diameter). As soils are damaged, natural aggregates (especially granular structure in A horizons) degrade to larger blocky structure or massive (cloddy) condition, accompanied by a loss of aggregate stability and formation of surface crusts. Besides direct compression during tillage, compaction is commonly associated with decreased organic matter because organic matter is critical in creating and maintaining stable soil structure. Compaction and degraded soil structure were associated with organic matter loss in the prehistorically farmed New Mexico soils previously discussed. Soil structure degradation has been reported in ancient agricultural fields in Europe as old as about 5,000 years.

Soil acidification and anthropogenic podzolization

Anthropogenic soil acidification and podzolization, including the development of iron-cemented horizons, have been inferred in the UK and elsewhere in northwestern Europe, where there is evidence from about 4,000 years ago to historic periods (e.g., Cunningham et al. 2001; Goudie, 2006). One mechanism seems to involve agriculture indirectly acting through climate and vegetation change. Deciduous forests were increasingly cleared for agriculture during the Bronze Age, but with a cooler wetter climate during the subsequent Iron Age, farms were abandoned. The climate no longer supported regeneration of the original woodland, and acidic heath vegetation took hold. This created conditions under which different soils developed: Spodosols with subsurface accumulations of organic-metal complexes and iron-cemented hardpans.

Salt and sodium accumulation

A common and widespread form of soil degradation associated with ancient through modern irrigation agriculture is the buildup of salt and sodium (Hillel, 1991; Goudie, 2006). This degradation is mostly associated with arid lands and results from poor-quality irrigation water and from rising water tables that bring salts near soil surfaces. Although there is evidence indicating serious salinity in ancient irrigation agriculture (Mesopotamia is the classic case), it is mainly inferred from data other than soil, such as written records indicating crop yield decline and increased use of salt-tolerant crops.

Hardening of highly weathered tropical soils – caused by agriculture?

Irreversible hardening of iron-rich, highly weathered soils (Oxisols) following exposure from cultivation has been inferred in some tropical areas, but this interpretation is controversial. Some observations of soil induration from agriculture seem valid, but the extent is far less than previously thought (Goudie, 2006). Most ironstone is now thought to have been naturally formed long before humans and agriculture and later exposed through erosion.

Summary

Several kinds of anthropogenic soil change from agriculture have been documented in the archaeological record. More research on ancient agricultural soils is needed because of the relative scarcity of quantitative soil studies, methodological limitations, the complexity of agricultural systems and soils, and imprints of multiple land use and environmental change.

Ancient agricultural soils are important sources of long-term information about soil change and related current agricultural challenges involving soil quality and conservation, water resources, climate change, and sustainability.

Bibliography

Bal, M.-C., Rendu, C., Ruas, M.-P., and Campmajo, P., 2010. Paleosol charcoal: reconstructing vegetation history in relation to agro-pastoral activities since the Neolithic. A case study in the eastern French Pyrenees. *Journal of Archaeological Science*, **37**, 1785–1797.

Beach, T., Luzzadder-Beach, S., Dunning, N., et al., 2009. A review of human and natural changes in Maya Lowland wetlands over the Holocene. *Quaternary Science Reviews*, **28**, 1710–1724.

Bell, M., and Boardman, J. (eds.), 1992. *Past and Present Soil Erosion: Archaeological and Geographical Perspectives*. Oxford: Oxbow books. Oxbow Monograph 22.

Bull, I. D., Betancourt, P. P., and Evershed, R. P., 2001. An organic geochemical investigation of the practice of manuring at a Minoan site on Pseira Island, Crete. *Geoarchaeology*, **16**, 223–242.

Cao, Z. H., Ding, J. L., Hu, Z. Y., et al., 2006. Ancient paddy soils from the Neolithic age in China's Yangtze River Delta. *Naturwissenschaften*, **93**, 232–236.

Courty, M. A., Goldberg, P., and Macphail, R. I., 1989. *Soils and Micromorphology in Archaeology*. Cambridge: Cambridge University Press.

Cunningham, D. A., Collins, J. F., and Cummins, T., 2001. Anthropogenically-triggered iron pan formation in some Irish soils over various time spans. *Catena*, **43**, 167–176.

Diamond, J., 2005. *Collapse: How Societies Choose to Succeed or Fail*. New York: Viking.

Erickson, C. L., 2000. The Lake Titicaca basin: a pre-Columbian built landscape. In Lenz, D. L. (ed.), *Imperfect Balance: Landscape Transformation in the Pre-Columbian Americas*. New York: Columbia University Press, pp. 311–356.

Goudie, A., 2006. *The Human Impact on the Natural Environment*. Malden: Blackwell.

Hartshorn, A. S., Chadwick, O. A., Vitousek, P. M., and Kirch, P. V., 2006. Prehistoric agricultural depletion of soil nutrients in Hawai'i. *Proceedings of the National Academy of Sciences*, **103**, 11092–11097.

Hesse, R., and Baade, J., 2009. Irrigation agriculture and the sedimentary record in the Palpa Valley, southern Peru. *Catena*, **77**, 119–129.

Hillel, D. J., 1991. *Out of the Earth: Civilization and the Life of the Soil*. Berkeley: University of California Press.
Holliday, V. T., 2004. *Soils in Archaeological Research*. New York: Oxford University Press.
Homburg, J. A., and Sandor, J. A., 2011. Anthropogenic effects on soil quality of ancient agricultural systems of the American Southwest. *Catena*, **85**, 144–154.
Houben, P., 2008. Scale linkage and contingency effects of field-scale and hillslope-scale controls of long-term soil erosion: anthropogeomorphic sediment flux in agricultural loess watersheds of southern Germany. *Geomorphology*, **101**, 172–191.
IUSS Working Group WRB, 2006. *World Reference Base for Soil Resources 2006*. Rome: FAO. World Soil Resources Reports No. 103.
Johnson, D. L., and Lewis, L. A., 1995. *Land Degradation: Creation and Destruction*. Oxford: Blackwell.
Kostyuchenko, V. P., and Lisitsyna, G. N., 1976. Genetic characteristics of ancient irrigated soils. *Soviet Soil Science*, **8**, 9–18.
Krahtopoulou, A., and Frederick, C., 2008. The stratigraphic implications of long-term terrace agriculture in dynamic landscapes: polycyclic terracing from Kythera Island, Greece. *Geoarchaeology*, **23**, 550–585.
Montgomery, D., 2007. *Dirt: The Erosion of Civilizations*. Berkeley: University of California Press.
Moorman, F. R., and van Breemen, N., 1978. *Rice: Soil, Water, Land*. Los Baños: International Rice Research Institute.
Sandor, J. A., 2006. Ancient agricultural terraces and soils. In Warkentin, B. (ed.), *Footprints in the Soil: People and Ideas in Soil History*. Amsterdam: Elsevier, pp. 505–534.
Sandor, J. A., and Eash, N. S., 1995. Ancient agricultural soils in the Andes of southern Peru. *Soil Science Society of America Journal*, **59**, 170–179.
Sandor, J., Burras, C. L., and Thompson, M., 2005. Factors of soil formation: human impacts. In Hillel, D. (ed.), *Encyclopedia of Soils in the Environment*. Oxford: Elsevier, pp. 520–532.
Zhang, G.-L., and Gong, Z.-T., 2003. Pedogenic evolution of paddy soils in different soil landscapes. *Geoderma*, **115**, 15–29.

Cross-references

Anthrosols
Canals and Aqueducts in the Ancient World
Ethnogeoarchaeology
Landscape Archaeology
Soil Geomorphology
Soil Micromorphology
Soil Stratigraphy
Soil Survey
Soils

SOUTHWESTERN US GEOARCHAEOLOGY

Gary Huckleberry
Department of Geosciences, University of Arizona, Tucson, AZ, USA

Definition

Application of earth science methods and concepts to archaeological research conducted in Arizona, New Mexico, and adjacent areas within the USA.

Introduction

Formal geoarchaeological research in the southwestern USA began in the 1920s and focused on geological dating and environmental reconstruction at archaeological sites. Today, geoarchaeological investigations address a variety of topics of interest to the academic and cultural resource management (CRM) communities. Those practicing geoarchaeology in the southwestern USA include geologists, geographers, soil scientists, and archaeologists. Studies of soils, geomorphology, and paleoclimate help to define the environmental context of the cultural record and provide a framework for assessing archaeological site visibility and preservation. Geoarchaeology also increases knowledge of the region's more than 4000 years history of agriculture, including the construction of waterworks for irrigation. Other geoarchaeological applications involve study of site formation processes and the manufacture and sourcing of artifacts and other cultural materials either composed of geological materials or containing chemical signatures related to geology. Geoarchaeological research conducted in the southwestern USA over the past ~25 years is briefly reviewed below.

Environmental context and site visibility

The earliest unequivocal cultural horizon in the southwestern USA begins ca. 13,000 years ago with Clovis at a time of tremendous environmental change associated with the end of the ice age. Geoarchaeological investigations of Paleoindian sites in the region have helped (1) determine the age of the earliest cultural deposits and (2) reconstruct landscape dynamics and paleoenvironment (Holliday et al., 2006; Haynes and Huckell, 2007; Ballenger et al., 2011). Many of these sites contain stratigraphic evidence of climatic and biogeographic change. Stratigraphy from Paleoindian sites in southeastern Arizona that records the Younger Dryas Chronozone, a period of rapid cooling, has provided data used to test the controversial extraterrestrial impact hypothesis (Surovell et al., 2009). Other early sites in the Southwest have been reanalyzed to clarify their stratigraphic integrity and determine the relationship between extinct Pleistocene fauna and humans (Waters, 1986; Huckell and Haynes, 2003).

Younger archaeological sites have also provided clues into past landscape dynamics, including episodes of accelerated eolian activity (Wright et al., 2011) and alluvial cycles marked by arroyo-cutting and channel backfilling (Waters and Haynes, 2001; Karlstrom, 2005). In combination with local geomorphological controls, climate variability, as manifested by changes in flood frequency and magnitude, appears to have played an important role in alluvial cycles, and human activity may have also played a role, especially after the development of agriculture and subsequent increased sedentism and construction of canals.

Archaeological site patterns are a product of both human behavior and geological processes. Changes in erosion and deposition through space and time have affected the preservation and visibility of the archaeological record in the southwestern USA and geoarchaeological research has helped to reconstruct past landscape changes so that the existing archaeological record can be better connected to past human mobility and subsistence. This concept applies not only to Paleoindian sites that have been subject to over 10,000 years of potential postdepositional disturbance but also to the more recent archaeological record (Ravesloot and Waters, 2004). An ongoing topic of geoarchaeological research in the southwestern USA is explaining why early agricultural sites dating to 4000–2000 years BP have yet to be identified in large arable floodplains of major perennial rivers like the Salt and Gila and why there is a paucity of pre-Hispanic canal systems along the Rio Grande. Such discrepancies may have geological rather than cultural explanations.

Geoarchaeology and agriculture

The effect of climate and landscape dynamics on the northward diffusion of domesticated plants from Mexico and the subsequent practice of agriculture in the southwestern USA continues to be a major theme in geoarchaeological research. Climate change, erosion, deposition, and soil formation created opportunities and challenges for indigenous farmers. The distribution of soils and landforms influenced cultivation strategies and placement of agricultural fields (Lightfoot, 1993; Dominguez and Kolm, 2005). These patterns were disrupted by landscape dynamics, particularly in floodplains subject to alluvial cycles. Past episodes of arroyo-cutting disrupted irrigation and have been linked to settlement changes and areas of abandonment (Force and Howell, 1997; Huckleberry and Duff, 2008; Anderson and Neff, 2011; Nials et al., 2011). Larger main stem rivers in lower elevations are less prone to arroyo-cutting but are subject to shifts between single and braided channel patterns that can also be disruptive to water control (Graybill et al., 2006).

Despite the vagaries of climate and landscape changes, agriculture persisted as a predominant subsistence strategy for several millennia in the southwestern USA. This has important implications regarding agricultural sustainability and the effects of prolonged food production on soil fertility. Some areas that supported prehistoric floodwater farming contain evidence of soils with enhanced fertility; whereas other areas contain soils with depleted nutrients relative to adjacent uncultivated soils (Homburg and Sandor, 2011). Likewise, soil quality was improved by prehistoric canal irrigation in some places (Schaafsma and Briggs, 2007); whereas in other areas, the accumulation of canal silt and clay in field areas reduced soil properties (e.g., permeability and bulk density) that are conducive to crop production (Huckleberry, 1992).

Due to the region's overall arid climate, most agriculture in the Southwest requires irrigation for successful crop production. A variety of irrigation strategies were employed, leaving a wide range of archaeological signatures preserved in the landscape. Geomorphology and alluvial stratigraphy are useful in the identification of ancient canals and reservoirs, and they help to understand how these features were constructed and how they functioned (Damp et al., 2002; Bayman et al., 2004). Insights into these ancient waterworks have also been gained from the study of biological materials contained within canals and reservoirs (Adams et al., 2002) and from recent developments in optically stimulated luminescence dating (OSL) of sediments and ceramics associated with irrigation deposits (Berger et al., 2009; Watkins et al., 2011). In some cases, remote sensing has been used to identify ancient agricultural features not readily visible at the surface (Berlin et al., 1990), and new developments in LiDAR technology offer great promise for recognizing subtle features in the landscape that relate to pre-Hispanic agriculture.

Site formation and materials analysis

Geoarchaeological research in the southwestern USA has helped reconstruct erosional, depositional, and postdepositional processes that have modified the cultural record. Many sites contain artifact distributions that were disrupted by natural biological and geological processes, a phenomenon that complicates reconstruction of past human behavior. Exactly how cultural materials have been modified by animal/root mixing, freeze-thaw, soil formation, and other surface dynamics is a topic of concern. Some environments/landforms are more dynamic than others. Given that much of the southwestern USA is arid, eolian landforms are common, and sand dunes that are prone to wind erosion (deflation) frequently consolidate artifacts from previously separate stratigraphic levels and in some cases may even invert stratigraphy such that older artifacts become emplaced over younger cultural deposits (Buck et al., 2002). Floodplains are also dynamic, and the region has a climate conducive to generating high energy, flash floods. Depending on water velocity and sediment load, floods may bury and preserve some cultural materials or transport and redeposit others. Sedimentary structures and grain-size distributions of alluvial deposits in bedrock and alluvial reaches of rivers provide insight into past floods and can be used to reconstruct physical site formation processes (Huckleberry, 2006; Draut et al., 2008). Most archaeological investigations that take place in dynamic geomorphic settings in the southwestern USA, where sites are likely to be buried or modified by surficial processes, usually include a geomorphologist or soil scientist to help interpret site formation processes.

Physical and chemical analysis of artifacts and other types of cultural material that can be related directly or indirectly to geology can also shed light on past human behavior. In the southwesten USA, this includes geochemical analysis of stone tools, ornaments, architecture, and food remains. Strontium isotopes have proven particularly useful at Chaco Canyon, where conifer wood beams (Reynolds et al., 2005) and maize (Benson et al., 2009) have been sourced to distant locations. Oxygen isotopes can be used to determine seasonality of marine shell harvesting in the northern Gulf of California that provided protein and ornamental material for trade (Foster et al., 2012). Mineralogical and geochemical signatures in obsidian (Shackley, 2005), turquoise (Hull et al., 2008), and ceramics (Abbott et al., 2008) help to reconstruct patterns of production, trade, and community interactions through time. Mineralogical and geochemical analyses of architectural adobe and natural soils provide clues to how Puebloan structures were constructed and how they might be stabilized and preserved (Rumsey and Drohan, 2011).

Rock art and constructed rock features such as geoglyphs common to the southwestern USA remain a topic of considerable archaeological interest but have been challenging to date. Pictographs are composed of pigments that often contain organic matter suitable for radiocarbon dating, although sampling is destructive to the art and thus discouraged. Petroglyphs are etched into rock coatings and in turn develop younger accretionary coatings (silica skins and rock varnish) that contain datable carbon (Russ et al., 1992). If carbon in the basal coating is not subject to postdepositional translocation or contamination by younger carbon and can be physically isolated and extracted, then a minimum age for the creation of the rock art can be ascertained. However, rock coatings are open systems, and it is difficult to meet these criteria. Moreover, this method also involves destructive sampling and compromises the rock art. Efforts at radiocarbon dating microlaminations on constructed rock features have yielded some success but are still considered experimental (Cerveny et al., 2006). Nondestructive and reliable methods for dating rock art and constructed rock features are a work in progress.

Summary

Geoarchaeology in the southwestern USA is practiced by people with diverse formal training and academic backgrounds who tend to be employed in academia or CRM (cultural resource management under both private and government auspices). Geoarchaeological research helps answer important questions regarding human adaptation and culture change in the southwestern USA since the end of the last ice age. This includes identification of biophysical processes and environmental changes that have influenced human behavior and modified the archaeological record. Geoarchaeology has also played an important role in identifying and understanding evidence for past human activity, thus assisting archaeologists and government agencies (city, county, tribal, state, and federal) manage cultural properties and resources. Although a considerable amount of geoarchaeological research conducted in the region has been published in books and peer-reviewed journals, considerably more has been published in less accessible "gray" literature (contract reports) associated with CRM. Fortunately, much of this literature is available at academic libraries within the southwestern USA.

Bibliography

Abbott, D. R., Lack, A. D., and Hackbarth, M. R., 2008. Provenance and microprobe assays of phyllite-tempered ceramics from the uplands of central Arizona. *Geoarchaeology*, **23**(2), 213–242.

Adams, K. R., Smith, S. J., and Palacios-Fest, M. R., 2002. *Pollen and Micro-Invertebrates from Modern Earthen Canals and Other Fluvial Environments Along the Middle Gila River, Central Arizona: Implications for Archaeological Interpretation*. Tucson: University of Arizona Press. Gila River Indian Community, Cultural Resource Management Program, Anthropological Research Paper 1.

Anderson, K. C., and Neff, T., 2011. The influence of paleofloods on archaeological settlement patterns during A.D. 1050–1170 along the Colorado River in the Grand Canyon, Arizona, USA. *Catena*, **85**(2), 168–186.

Ballenger, J. A. M., Holliday, V. T., Kowler, A. L., Reitze, W. T., Prasciunas, M. M., Miller, D. S., and Windingstad, J. D., 2011. Evidence for Younger Dryas global climate oscillation and human response in the American southwest. *Quaternary International*, **242**(2), 502–519.

Bayman, J. M., Palacios-Fest, M. R., Fish, S. K., and Huckell, L. W., 2004. The paleoecology and archaeology of long-term water storage in a Hohokam reservoir, southwestern Arizona, U.S.A. *Geoarchaeology*, **19**(2), 119–140.

Benson, L. V., Stein, J. R., and Taylor, H. E., 2009. Possible sources of archaeological maize found in Chaco Canyon and Aztec Ruin, New Mexico. *Journal of Archaeological Science*, **36**(2), 387–407.

Berger, G. W., Post, S., and Wenker, C., 2009. Single and multigrain quartz-luminescence dating of irrigation-channel features in Santa Fe, New Mexico. *Geoarchaeology*, **24**(4), 383–401.

Berlin, G. L., Salas, D. E., and Geib, P. R., 1990. A prehistoric Sinagua agricultural site in the ashfall zone of Sunset Crater, Arizona. *Journal of Field Archaeology*, **17**, 1–16.

Buck, B. J., Kipp, J., Jr., and Monger, H. C., 2002. Inverted clast stratigraphy in an eolian archaeological environment. *Geoarchaeology*, **17**(7), 665–687.

Cerveny, N. V., Kaldenberg, R., Reed, J., Whitley, D. S., Simon, J., and Dorn, R. I., 2006. A new strategy for analyzing the chronometry of constructed rock features in deserts. *Geoarchaeology*, **21**(3), 281–303.

Damp, J. E., Hall, S. A., and Smith, S. J., 2002. Early irrigation on the Colorado Plateau near Zuni Pueblo, New Mexico. *American Antiquity*, **67**(4), 665–676.

Dominguez, S., and Kolm, K. E., 2005. Beyond water harvesting: a soil hydrology perspective on traditional southwestern agricultural technology. *American Antiquity*, **70**(4), 732–765.

Draut, A. E., Rubin, D. M., Dierker, J. L., Fairley, H. C., Griffiths, R. E., Hazel, J. E., Jr., Hunter, R. E., Kohl, K., Leap, L. M., Nials, F. L., Topping, D. J., and Yeatts, M., 2008. Application of sedimentary-structure interpretation to geoarchaeological investigations in the Colorado River Corridor, Grand Canyon, Arizona, USA. *Geomorphology*, **101**(3), 497–509.

Force, E. R., and Howell, W. K., 1997. *Holocene Depositional History and Anasazi Occupation in McElmo Canyon, Southwestern Colorado*. Tucson: Arizona State Museum, University of Arizona. Arizona State Museum Archaeological Series 188.

Foster, M. S., Mitchell, D. R., Huckleberry, G., Dettman, D., and Adams, K. R., 2012. Archaic period shell middens, sea-level fluctuation, and seasonality: archaeology along the northern

Gulf of California littoral, Sonora, Mexico. *American Antiquity*, **77**(4), 756–772.
Graybill, D. A., Gregory, D. A., Funkhauser, G., and Nials, F. L., 2006. Long-term streamflow reconstructions, river channel morphology, and aboriginal irrigation systems along the Salt and Gila Rivers. In Doyel, D. E., and Dean, J. S. (eds.), *Environmental Change and Human Adaptation in the Ancient Southwest*. Salt Lake City: University of Utah Press, pp. 69–123.
Haynes, C. V., and Huckell, B. (eds.), 2007. *Murray Springs: A Clovis Site with Multiple Activity Areas in the San Pedro Valley, Arizona*. Tucson: University of Arizona Press. Anthropological Papers, University of Arizona 71.
Holliday, V. T., Huckell, B. B., Mayer, J. H., Forman, S. L., and McFadden, L. D., 2006. Geoarchaeology of the Boca Negra Wash area, Albuquerque Basin, New Mexico, USA. *Geoarchaeology*, **21**(8), 765–802.
Homburg, J. A., and Sandor, J. A., 2011. Anthropogenic effects on soil quality of ancient agricultural systems of the American southwest. *Catena*, **85**(2), 144–154.
Huckell, B. B., and Haynes, C. V., Jr., 2003. The Ventana Complex: new dates and new ideas on its place in early Holocene western prehistory. *American Antiquity*, **68**(2), 353–371.
Huckleberry, G. A., 1992. Soil evidence of Hohokam irrigation in the Salt River Valley, Arizona. *Kiva*, **57**(3), 237–249.
Huckleberry, G. A., 2006. Sediments. In Balme, J., and Paterson, A. (eds.), *Archaeology in Practice: A Student Guide to Archaeological Analysis*. Malden: Blackwell, pp. 338–361.
Huckleberry, G., and Duff, A. I., 2008. Alluvial cycles, climate, and puebloan settlement shifts near Zuni Salt Lake, New Mexico, USA. *Geoarchaeology*, **23**(1), 107–130.
Hull, S., Fayek, M., Mathien, F. J., Shelley, P., and Durand, K. R., 2008. A new approach to determining the geological provenance of turquoise artifacts using hydrogen and copper stable isotopes. *Journal of Archaeological Science*, **35**(5), 1355–1369.
Karlstrom, E. T., 2005. Late Quaternary landscape history and geoarchaeology of two drainages on Black Mesa, northeastern Arizona, USA. *Geoarchaeology*, **20**(1), 1–28.
Lightfoot, D. R., 1993. The landscape context of Anasazi pebble-mulched fields in the Galisteo Basin, northern New Mexico. *Geoarchaeology*, **8**(5), 349–370.
Nials, F. L., Gregory, D. A., and Hill, J. B., 2011. The stream reach concept and the macro-scale study of riverine agriculture in arid and semiarid environments. *Geoarchaeology*, **26**(5), 724–761.
Ravesloot, J. C., and Waters, M. R., 2004. Geoarchaeology and archaeological site patterning on the middle Gila River, Arizona. *Journal of Field Archaeology*, **29**(1–2), 203–214.
Reynolds, A. C., Betancourt, J. L., Quade, J., Patchett, P. J., Dean, J. S., and Stein, J., 2005. $^{87}Sr/^{86}Sr$ sourcing of ponderosa pine used in Anasazi great house construction at Chaco Canyon, New Mexico. *Journal of Archaeological Science*, **32**(7), 1061–1075.
Rumsey, S. D., and Drohan, P. J., 2011. Cultural implications of architectural mortar selection at Mesa Verde National Park, Colorado. *Geoarchaeology*, **26**(4), 544–583.
Russ, J., Hyman, M., and Rowe, M. W., 1992. Direct radiocarbon dating of rock art. *Radiocarbon*, **34**(3), 867–872.
Schaafsma, H., and Briggs, J. M., 2007. Hohokam field building: silt fields in the northern Phoenix Basin. *Kiva*, **72**(4), 431–457.
Shackley, M. S., 2005. *Obsidian: Geology and Archaeology in the North American Southwest*. Tucson: University of Arizona Press.
Surovell, T. A., Holliday, V. T., Gingerich, J. A. M., Ketron, C., Haynes, C. V., Jr., Hilman, I., Wagner, D. P., Johnson, E., and Claeys, P., 2009. An independent evaluation of the Younger Dryas extraterrestrial impact hypothesis. *Proceedings of the National Academy of Sciences*, **106**(43), 18155–18158.
Waters, M. R., 1986. *The Geoarchaeology of Whitewater Draw, Arizona*. Tucson: University of Arizona Press. Anthropological Papers, University of Arizona 45.
Waters, M. R., and Haynes, C. V., Jr., 2001. Late Quaternary arroyo formation and climate change in the American southwest. *Geology*, **29**(5), 399–402.
Watkins, C. N., Rice, G. E., and Steinbach, E., 2011. Dating Hohokam canals: a methodological case study. *Journal of Arizona Archaeology*, **1**(2), 162–168.
Wright, D. K., Forman, S. L., Waters, M. R., and Ravesloot, J. C., 2011. Holocene eolian activity as a proxy for broad-scale landscape change on the Gila River Indian Community, Arizona. *Quaternary Research*, **76**(1), 10–21.

Cross-references

Alluvial Settings
Canals and Aqueducts in the Ancient World
Ceramics
Chronostratigraphy
Climatostratigraphy
Eolian Settings: Sand
Geochemical Sourcing
Geomorphology
Grain Size Analysis
Optically Stimulated Luminescence (OSL) Dating
Oxygen Isotopes
Paleoenvironmental Reconstruction
Petroglyphs
Radiocarbon Dating
Remote Sensing in Archaeology
Sedimentology
Site Formation Processes
Soils, Agricultural
Strontium Isotopes

SPELEOTHEMS

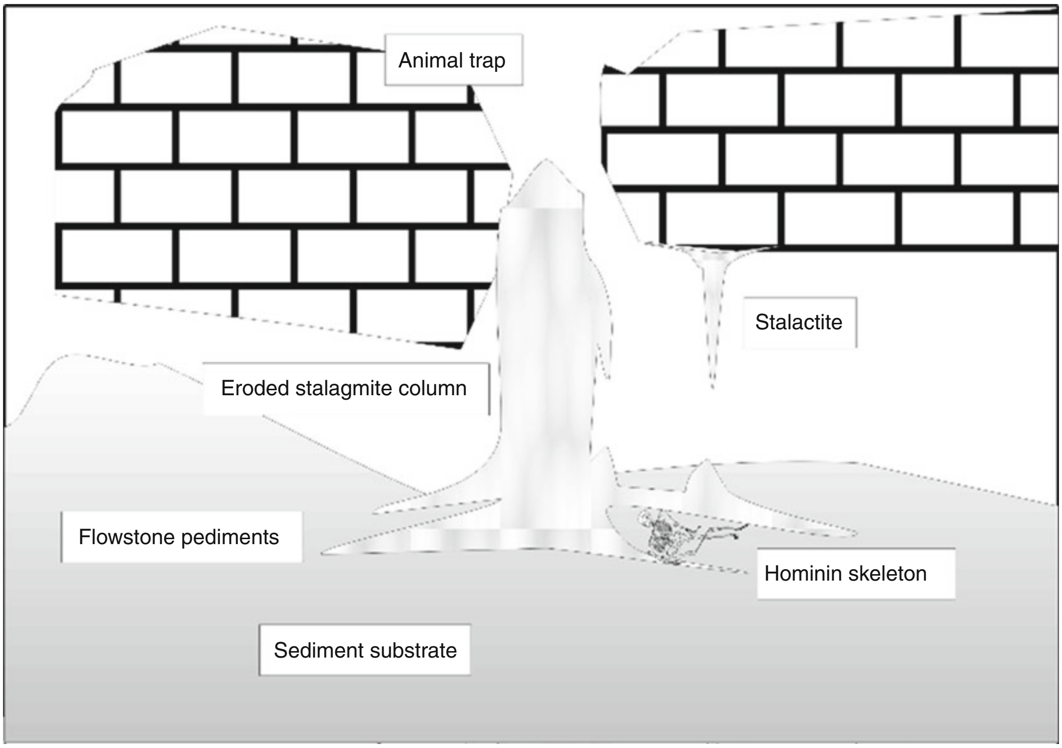
Alfred G. Latham
Archaeology, Classics and Egyptology, Liverpool University, Liverpool, UK

Definition

The term speleothem is used to cover all secondary chemical deposits in caves and, occasionally, of mines in limestone (karst) terrains. Its etymology is from the Greek "spēlaion" (or cave) and "thema" (or deposit). For a more specialist account of karst and speleology, see Ford and Williams (2007).

Introduction

Most people are familiar with the commonest forms of speleothems: stalactites, stalagmites, and flowstones. Their main relevance to the archaeology of caves stems from (1) their association with hominin and faunal remains or with artifacts such as stone tools, (2) the continuous records of climate change they contain, and (3) the fact that they can be reliably dated back hundreds of thousands of years and, in some cases, even millions of years. Thus, the dating of speleothems has contributed significantly to constructing a chronology of the stages of human evolution. This is because hominin remains are frequently



Speleothems, Figure 1 Stalactite, stalagmite, and flowstone are displayed in a diagram showing the growth relationship between the three main types of speleothems and their possible relationship to artifacts and hominin remains. The skeleton in the scenario represents a location similar to that of Little Foot from Sterkfontein, South Africa, which was sandwiched between flowstone layers in the Silberberg Grotto. The upper flow actually bisected and formed underneath part of the australopithecine skeleton after it had slumped on breccia and flowstone.

well preserved in the alkaline environment of caves where speleothems also form, and the pace of human evolution, of climate change, and of karst processes (geomorphological processes in limestone terrains) are commensurate in scale. Caves may also contain speleothems that are not directly related to their archeologically significant layers, and, in such cases, these speleothems may provide relative *ante quem* and *post quem* ages.

Isotope signatures of oxygen and carbon from speleothems have yielded proxy records of changes in climate and ecology for the Quaternary and even earlier periods, and such records are significant in documenting changing environments over the course of human evolution. In addition, speleothems, along with various clastic deposits, provide data for site reconstruction. Many caves show alternations of animal denning and human occupation, and some parts of caves may have acted as animal traps – into which animals fall accidentally and create a fossil record with their accumulated skeletons – as shown in Figure 1.

The importance of speleothems for cave archaeology was indicated very early in the history of excavation by discoveries at Kents Cavern, Torquay, on the south coast of England. Father John McEnery (or MacEnery) excavated stone tools associated with extinct fauna when he broke through a stalagmite-flowstone floor, whose underlying layers provided the first hard evidence for the antiquity of man, though his inferences were not immediately accepted. His excavations took place between 1824 and 1829, 30 years before Darwin published his famous treatise *On the Origin of Species* in 1859. The flowstone-capped layers that contained Acheulian bifaces have been dated to 400–450 ka by the Thermal Ionization Mass Spectrometry, or TIMS, U-series method (McFarlane and Lundberg, 2005; Lundberg and McFarlane, 2007).

By far, the most common mineralogy of speleothems is calcium carbonate, $CaCO_3$, but two crystalline forms are possible: one being calcite (single crystals are known as Iceland Spar) and the other aragonite. The next most common mineral in caves is gypsum, $CaSO_4 \cdot 2H_2O$, a calcium sulfate. There are many other mineral speleothems (Hill and Forti, 1997), though they are seldom associated with fossil bones or artifacts relevant to archaeology.

Carbonate speleothems form from carbonate-rich seepage water as it passes through the soil zones at the surface and into the underlying limestone via cracks in the rock. A related rock type, dolomite, is also found widely, as in

South Africa; whereas limestone is carbonate $CaCO_3$, in dolomite, magnesium (Mg) replaces many of the Ca ions. Carbon dioxide outgases from the feedwater, which contains calcium and bicarbonate (hydrogen carbonate) ions, as it emanates from the rock into the cave passage thus causing the calcium carbonate to precipitate.

$$Ca^{2+} + 2HCO_{3-} \rightarrow CaCO_3 + CO_2\uparrow + H_2O$$

This is not an evaporative process because the atmospheres of most cave interiors are at, or close to, water vapor saturation. But some speleothems do form by the evaporation of dripwater in drafty passages and in well-aerated cave entrances. Those speleothems that formed with the larger aragonite structure may later revert to the more compact calcite form in the presence of water.

Of its many different forms, speleothems occur in three main types (Figure 1).

1. Stalactites form from dripwater at the ceiling and often begin as hollow straws from precipitation around the rim of the drip. When the feedwater moves to the outside, they may subsequently "bulk out" as long narrow cones, or they may form curtains on the underside of sloping ceilings and walls. They are occasionally associated with archeological evidence. In caves known for prehistoric cave paintings, ribbon-like deposits may form down the walls and so may be seen to postdate or antedate the wall paintings. They have provided U–Th dates by the TIMS method because it requires only small samples, as at Tito Bustillo and other caves in Northern Spain (Pike et al., 2012). Most cave paintings dated so far have been by the radiocarbon method on pigment or on associated artifacts. At Arcy-sur-Cure, near Avallon, France, sheet-like coverings on the walls have helped to preserve cave paintings of mammoths and other fauna.
2. Stalagmites form on the floor, either on solid rock or on sediment. In the latter case, the early layers at the bottom of the stalagmite may be contaminated with mud or sand. Stalagmites grow upwards where the calcite layers form long-sided caps. The drip centers occasionally show "work holes" at the impact point, which may or may not have some sediment in them depending on whether the stalagmites are within reach of cave flood water. When stalagmites join with their parent stalactites, they form columns.
3. Flowstones occur in sheet-like forms that grow from the trickle of carbonate water down local slopes. Most of them are associated with rimstone pools (or rimstone dams; also called gours), and they tend to form overlapping cascades. In warmer climates, where chemical reactions are faster, the gours commonly grow to several meters across and as much deep. Flowstones often display micro-gours of a few centimeters or less across.
4. Moonmilk is a noncrystalline flowstone deposit that is thought to form in the presence of bacteria. As it is porous, it is usually not suitable for dating.

Both stalagmites and flowstones can form part of the floor deposits and so are more closely associated with any archeological contexts than are stalactites. Some references, given below, also refer to hot spring deposits, such as spongy tufas that once contained vegetation, but which consist mainly of a carbonate component. As some of them are associated with hominin remains and archeological finds, they may also be dated by U-series and other methods. The main problem is that they also contain detrital components such as windblown sediments, so they have to be treated as contaminated deposits as discussed below.

Pure calcite is translucent, but dissolved elements and minerals may impart color to the forms. The hues are most frequently produced by iron (Fe): red to yellow; manganese (Mn): black; copper (Cu): blue; or varied organic substances: black to brown to yellow to red (Figure 2). Particle impurities of clastic sediment such as mud, clay, or silt form colored opaque layers. The sediment that coated the long stalagmite of Figure 2a (left) was partly washed off down the sides, giving it the grayer appearance. Tiny holes that are filled with air, water, and water vapor are called fluid inclusions; if they are sufficiently dense, they impart a more milky appearance to the calcite. The importance of fluid inclusions lies in their much-studied potential for paleoclimate and paleoecology research that is, in turn, important for an understanding of environmental change in the context of faunal and human evolution.

Dating

The sources of the carbon in the $CaCO_3$ that crystallizes into speleothems are partly the host rock and partly the organic soil zone. The feedwater, however, can continue to exchange carbon before the mineral finally precipitates, so the ^{14}C component derived from organic materials is diluted by variable amounts of carbon contributed by the rock. Radiocarbon dating is limited to ages below about 60 ka, and thus, it is seldom used for dating speleothems. Instead, U–Th dating of speleothems, and particularly of corals, has been used to calibrate the ^{14}C scale back to 60 ka (Weninger and Jöris, 2008).

The main dating techniques for speleothems have utilized the decay series based on naturally occurring radioactive ^{238}U which, being soluble in water, coprecipitates with each newly formed layer of calcite or aragonite. For various applications of U-series methods and details, see Ivanovich and Harmon (1992) or Bourdon et al. (2003). ^{238}U decays by a series of alpha and beta particle emissions, first to ^{234}U and ^{230}Th, and eventually to ^{208}Pb, a stable isotope of lead (Figure 3). The most commonly used dating method is known as U–Th dating. It is based on the observation that the ^{238}U granddaughter, ^{230}Th, is insoluble in water and, therefore, it is always absent in each new layer of a speleothem, which therefore constitutes a reset clock in which the radiogenic ^{230}Th, having a half-life of 75,200 years, grows from zero toward equilibrium with ^{234}U and ^{238}U at a known rate (Figure 4).

Speleothems, Figure 2 The 76 cm-long stalagmite (**a**; *left*) grew from 1,300 years ago to the present. It formed on a sediment bank and was actively forming when sampled. It contains organics (which give it the amber color) and flood-borne detritus, some of which has been washed off to the sides by the dripwater. The markings are in preparation for cutting into subsamples for magnetometry. The 18 cm purer speleothem (**b**; *right*) has been sectioned to show growth layers and crystal growth. Crystals grew at right angles to the morphology of the growth surfaces, hence the curvature, and are said to have a palisade texture with generally elongated crystals.

In the laboratory, a few grams or less of a sample are chipped out and dissolved (as in the small stalagmite in Figure 1). Then, the U, Th, or Pb isotopes are separated by ion-exchange resins before deposition onto spectrometer filaments prior to ionization. Analysis of the U and Th isotopes, which gives the age, involves the chemical separation of these isotopes before measuring their relative abundances by alpha-particle spectrometry or by mass spectrometry. Isotope tracers of the same elements, colloquially known as isotope spikes, are used to trace and correct for different chemical yields in the laboratory process known as isotope dilution analysis.

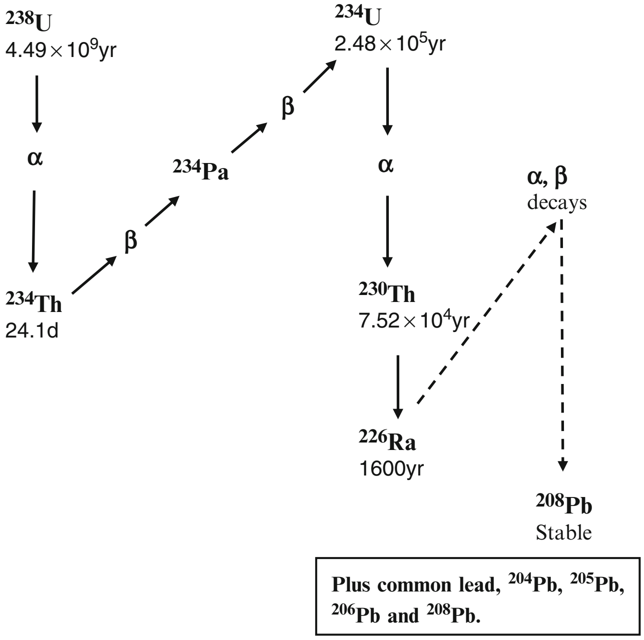
The equation yielding the age for the U–Th method from the isotope ratios is given by Eq. 1:

$$^{230}Th^{234}U = \frac{\frac{1-e^{-\lambda_{230}t}}{^{234}U}}{^{238}U + \frac{\lambda_{230}}{\lambda_{230}-\lambda_{234}}\left(1-\frac{\frac{1}{^{234}U}}{^{238}U}\right)\left(1-e^{-(\lambda_{230}-\lambda_{234})t}\right)} \qquad (1)$$

and t, the age, is worked out using a computer program. λ_{230} and λ_{234} are the activity coefficients (decay constants) of ^{230}Th and ^{234}U.

Older published U–Th ages relied on the alpha-particle emissions of the different isotopes and were counted on semiconductor detectors in which the age limit of the method was 400,000 years for samples with high U concentration. The advent of TIMS and related mass spectrometric techniques (from about 1990 onward), in which individual atoms are counted, has higher precision; its U–Th dating limit is about 600,000 years and, instead of chipping out sample layers of several grams for alpha spectrometry, less than a gram is needed for TIMS.

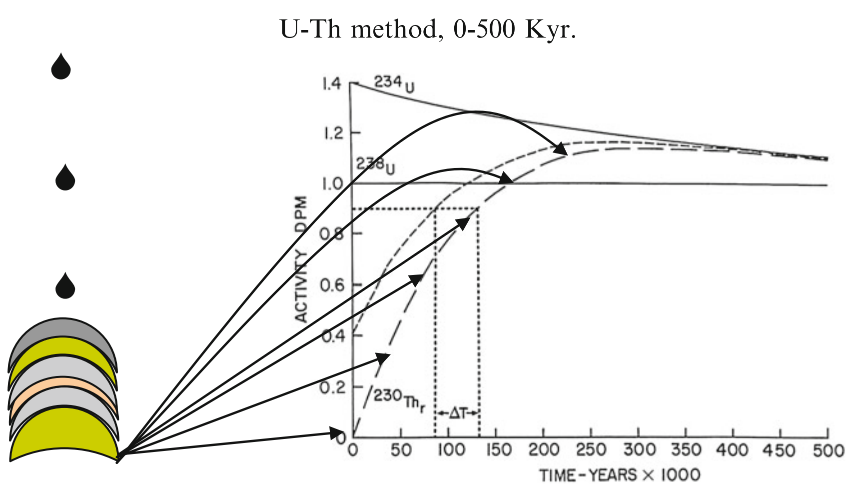
The South African caves around Johannesburg have yielded many hominin remains of *Australopithecus africanus*, *Paranthropus robustus* (or *A. robustus*, a common synonym), *Homo habilis*, and related forms. There are many such sites in South Africa that remain to be examined, and it has become clear that in the period 3–1.5 Ma, the region appears to have witnessed the existence, and possibly even the evolution, of several hominin species. Previously, these hominins were very difficult to date, and consequently, they were somewhat neglected in studies of human evolution.



Speleothems, Figure 3 The radioactive decay schemes from ^{238}U to ^{208}Pb with the relevant half-lives. The details of the more rapid alpha and beta decays from ^{226}Ra (radium) to ^{208}Pb are not shown. Alpha-particles are two neutrons plus two protons, as in a helium nucleus, and hence the resulting atom from alpha decay has an atomic mass four less than the parent. Electrons possess 1/1800 the mass of a nucleon, so there is effectively no mass change in beta decay.

Their importance demanded a means of determining their age, and so the geological chronometry based on the buildup of ^{208}Pb in the ^{238}U decay series has been adapted in cases where concentrations of uranium in speleothems are sufficiently high. In this method, the clock depends upon the decay of ^{238}U to ^{208}Pb. As ^{238}U has a very long half-life of 4.49×10^9 years (Figure 3), amounts of accumulated ^{208}Pb are small. Allowance also has to be made for the contribution of ^{208}Pb that coprecipitated from the feedwater as the so-called common lead. This is done using either the non-radiogenic index isotope, ^{204}Pb, or the radiogenic ^{205}Pb that can be produced by its radiogenic parent, ^{235}U, but occurs in such small quantities from this source that most of the measured ^{205}Pb can be counted as belonging to common lead. The method involves plotting the different concentrations of ^{238}U relative to the common lead in a so-called isochron plot that provides a robust measure of the precision of the age estimates.

Measurement precision errors are propagated to the final age estimates by sophisticated error-handling programs that take into account that some of the errors are correlated. It was common in alpha spectrometry to quote age errors to one standard deviation, known as one sigma (1σ). TIMS-based ages are often quoted to two sigma (2σ). Because of the nature of the growth curve, U–Th ages often have a $+1\sigma$ error that is greater than the -1σ error. The TIMS precision is usually better than 1 % of the age, and thus, a typical age quote for the interglacial thermal maximum of the faunal stage known as the



Speleothems, Figure 4 Growth to equilibrium graph showing how ^{230}Th grows from zero to equilibrium with its parent ^{234}U and then grandparent ^{238}U in a given layer of calcite. If there is initial ^{230}Th detritus, then the effect leads to an apparent increase in age by ΔT. Multiple leachate methods may be used to correct for detrital contamination.

Ipswichian, measured using coral samples from the Barbados Terrace III and corresponding to Marine Isotope Stage 5e, would be 124.0 $^{+1.2}/_{-1.0}$ ka. (Note: absolute time is ka, periods of time are in kyr).

The success, accuracy, and precision of these methods are dependent upon four factors:

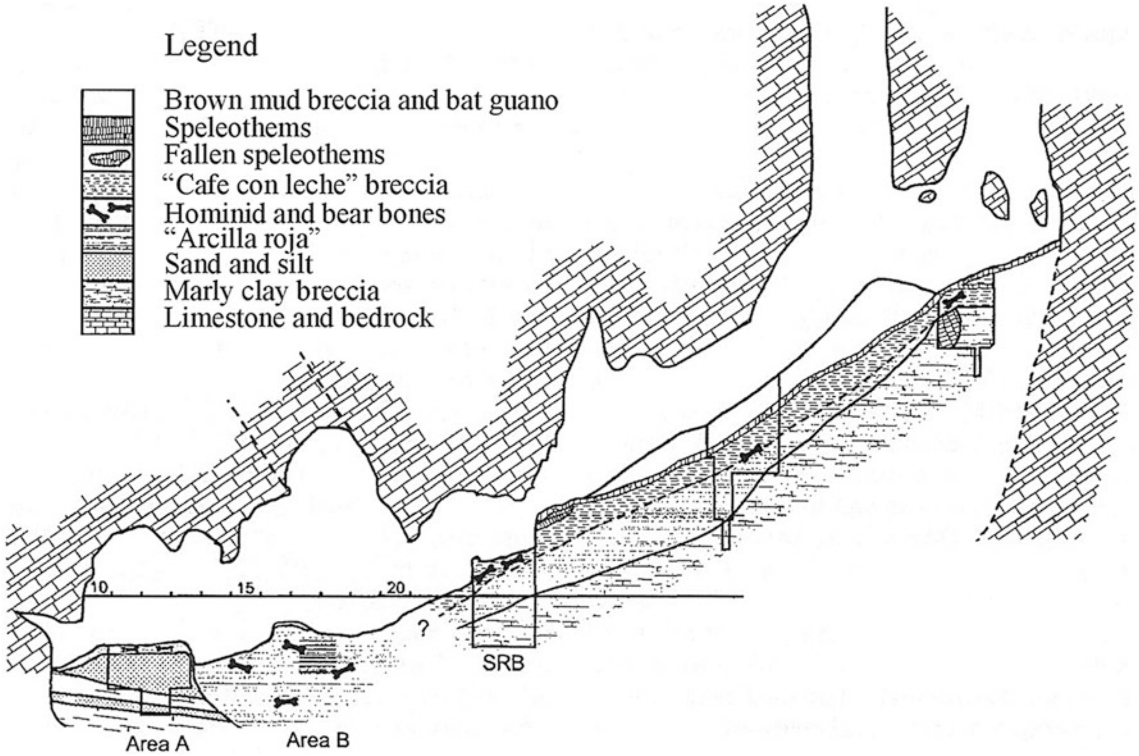
1. Having a sufficient concentration of U – the higher the U, the better the precision in determining the age. Concentrations of U in speleothems are typically in the range of 0.1–10 parts per million (ppm).
2. Knowing the excess of an intermediate decay product, such as ^{234}U, that also contributes to ^{230}Th and to ^{208}Pb – these are usually measured in the same or related analysis. For U–Pb dating, the contribution of ^{208}Pb from the original excess of ^{234}U becomes harder to assess with increasing age. This is because the remaining excess ^{234}U diminishes, making it harder to measure beyond an age limit of 3 Ma.
3. Making an allowance for additional isotopes from any detritus – these can usually be allowed for by analysis of five or more subsamples having varied proportions of the two using isochron plots, but it takes longer to do (Schwarcz and Latham, 1989). For publications before about 1988, age corrections used ^{232}Th as an index for the extra detrital ^{230}Th but not for the extra U isotopes, and so they were only approximate.
4. Ensuring that the system has been closed to migration, in or out, of any of the decay-series isotopes. The transgression of this closed-system assumption is detectable from daughter isotopes in excess of their parents and from anomalous isochrons. It is usually not possible to make allowance for an open-system history unless it can be demonstrated that isotope migration was regular with time such that it can be modeled. Experience has shown that movement of isotopes appears to have occurred at some later stage when speleothems lose some of the U upon recrystallization of aragonite to calcite.

Although U–Pb and U–Th have the same parent, ^{238}U, the daughter products and half-lives are different, and the clocks based on them are independent. Cliff et al. (2010) showed that there was good concordance on a U-rich speleothem from Spannagel Cave (Austrian Alps) between U–Pb and U–Th ages, respectively: 267 ± 1 ka versus 267 ± 5 ka; 291 ± 1 versus 295 ± 11 ka; and 340 ± 2 versus 353 ± 9 ka.

Some archeological caves, such as the South African australopithecine sites, are sufficiently old (on the order of several million years) that their deposits, including flowstones, may have recorded reversals of the Earth's magnetic field. The last main reversal was at 780 ka when the Earth's magnetic field changed from the reversed Matuyama chronozone to the normal Brunhes chronozone. Cave reversal records might be amenable to dating by finding a match to a part of the age-calibrated Global Polarity Time Scale (GPTS) (Gradstein et al., 2012). Neither speleothems nor sedimentary layers are deposited at uniform rates – there may indeed have been depositional hiatuses – and it is not to be expected that their records will be sufficiently long for them to be used as a match on their own. Therefore, another dating method (e.g., from time-sensitive faunal assemblages) is usually required to locate roughly where the match in the GPTS is located. Speleothems must also contain sufficient quantities of iron oxide grains such as magnetite or hematite; otherwise, most speleothems are too pure to provide a measurable characteristic remanent magnetization (ChRM, the stable part of the natural remanent magnetization, NRM). It is pertinent to point out here that if the clastic deposits of caves are to contribute to the reversal record, they must have been laid down subaqueously so that the Earth's magnetic field can influence the direction of settling of the magnetized particles within a depth of water of at least a few centimeters. That is, sediments that have resulted from slumps or debris flows are unlikely to present a faithful reversal record. Flowstones do allow a faithful recording of the ambient magnetic field (Latham et al., 1979; Latham and Ford, 1993).

Applications

The search for speleothems associated with hominin remains and artifacts that could be studied for chronological purposes is now a routine part of archeological cave excavations. The initial development of the U–Th method on speleothems was due to the Russian, V. V. Cherdyntsev (Ivanovich and Harmon, 1992). He applied it to dating the hot spring deposits of Middle Paleolithic Age at Vértesszöllös (Hungary) and at other middle European sites. John Rosholt at the United States Geological Survey made significant contributions in the early 1980s using new isotope dilution techniques to date contaminated precipitations that helped to extend the method to contaminated samples such as those at Vértesszöllös. The McMaster University laboratory in Canada run by Henry Schwarcz and Derek Ford maintained a program from 1973 (for over 35 years) of U–Th dating of carbonate speleothems and hot spring deposits, many of which were directly related to solving chronological problems associated with the Middle and Upper Paleolithic in Europe and Israel. Their work also included related paleoenvironmental and landform studies. Early U–Th dating studies included sites of the Middle Paleolithic such as La Chaise-de-Vouthon, France (Blackwell et al., 1983); Grotte du Lazaret, Nice, France (Falguères et al., 1992); analysis and reanalysis at Caune de l'Arago, France, Tautavel, Eastern Pyrenees (Falguères et al., 2004); Vértesszöllös, Hungary, using U–Th and paleomagnetism (Schwarcz and Latham, 1984); Tata, Hungary (Schwarcz and Skoflek, 1982); Bilzingsleben, Germany, using U–Th and ESR (Schwarcz et al., 1988); Pontnewydd, Wales, using U–Th and TL (Green et al., 1981); and Petralona, Greece, using U–Th and paleomagnetism (Latham and Schwarcz, 1992). Several Iberian cave sites have been dated by Jim Bischoff – Arbreda, by ^{14}C



Speleothems, Figure 5 The Sima de los Huesos pit (Burgos, Spain) and its hominin remains in relation to the capping flowstone layers. The dates in the text refer to the capping flowstones and the magnetic reversals to the underlying sediments (From Bischoff et al., 2003).

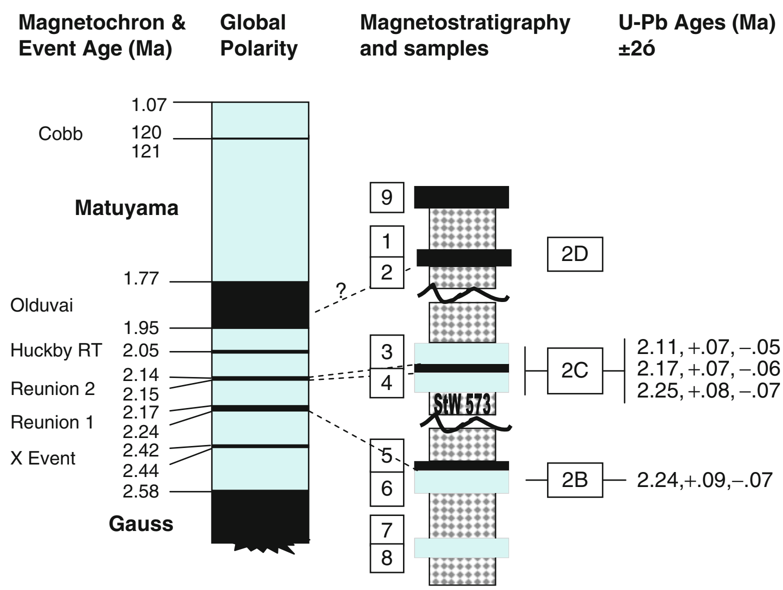
(Bischoff et al., 1989); El Castillo (Bischoff et al., 1992); Abric Romaní (Bischoff et al., 1994) – in the knowledge that several of them contain information on the origin and fate of Neanderthals in Western Europe.

For human evolution studies from cave sites, Ann Wintle, Hélène Valladas, Rainer Grün, and others also developed radiation dose methods of thermoluminescence (TL) and optically stimulated luminescence (OSL), as well as related methods, on burnt flint and of electron spin resonance (ESR) dating on tooth enamel.

Unfortunately, not all caves contain speleothems useful for dating archeological remains. One of the most important localities with sites recording the Middle to Upper Paleolithic transition is the Mount Carmel caves near Haifa, Israel, that had been excavated by the Cambridge University archeologist Dorothy Garrod, and associates from 1924 to 1936. These are Et-Tabun, El-Wad, Es-Skhul, Jamal, and some 13 km to the south, Kebara Cave. The use of speleothems from these sites was compromised by significant alteration that had removed both bone and speleothems through the oxidation of overlying guano deposits and destructive acids released in the process. Nearly all of the samples taken had experienced a degree of open-system movement of isotopes. These Levantine caves have instead yielded results to dating applications using ESR and TL, though not without a considerable amount of reanalysis. One Middle Paleolithic (Amudian) site further south at Qesem (near Tel Aviv) contained speleothems that have produced U–Th ages of 382–200 ka, spanning the Lower Paleolithic Acheulian to the Mousterian (Barkai et al., 2003).

Excavation and reanalysis at the Israeli sites has involved teams of chronologists and researchers familiar with cave deposits. As this was not the case in many other sites, uncertainty still surrounds the stratigraphy and age of the Petralona skull, for example, from northern Greece, which possesses both *H. erectus* and Neanderthal affinities. Related flowstone layers have been dated by U–Th and other methods; the skull is likely to be older, perhaps twice the quoted youngest age of around 170 ka (Latham and Schwarcz, 1992).

Atapuerca near Burgos, Spain, comprises several cave sites such as Trinchera Dolina and Elefante that have yielded remains of *Homo antecessor*, dated to 1.3–1.0 Ma by the magnetic reversal sequence of clastic sediments. Nearby Sima de los Huesos is a 10 m deep pit that has yielded the remains of over 34 individuals of a pre-Neanderthal stage (Figure 5). The remains lay underneath a flowstone floor. Initial attempts to date the flowstone combined U–Th alpha spectrometry with



Speleothems, Figure 6 The U–Th ages and magnetic polarity placement in the Global Polarity Time Scale of the flowstones above and below Little Foot (StW 573) of the Silberberg Grotto of Sterkfontein, from Walker et al. (2006). "Huckby RT" refers to the Huckleberry Ridge tuff event. In the Global Polarity graph, black sections represent normal polarity intervals, while the lighter blue color designates reversed polarity.

paleomagnetic polarity analysis. The age estimate was at or above the U–Th dating limit of 400 ka, but the polarity of the underlying sediments was normal, which was taken to mean that the remains were older than 400 ka but not older than the Brunhes-Matuyama boundary at 780 ka (Bischoff et al., 2003). Subsequently, a higher resolution TIMS reanalysis on samples from the flowstone suggested ages around 600 ka (Bischoff et al., 2007).

Little Foot is the name given to remains of an almost complete australopithecine (possibly *Australopithecus africanus*) enclosed in flowstone layers in the Silberberg Grotto of Sterkfontein Cave near Johannesburg, South Africa. The individual appears to have fallen down the side of a large stalagmite, and subsequently, the skeleton became covered in a calcite flow and red silts derived from the surface. Based upon the fossil morphology, its position in the cave, and the evidence of the breccia infill, it was initially estimated to be around 3 Ma in age. Attempts to date adjacent flowstone layers underlying and overlying Little Foot included a magnetic polarity sequence on the flowstones aided by biochronology, which yielded an age around 3.2 Ma and then by assays of cosmogenically produced ^{10}Be and ^{26}Al in clastic sediments, which yielded an age estimate of 4.2 Ma (Granger and Muzikar, 2001; Partridge et al., 2003). These estimates were thought to be too old, as the faunal assemblages were little different from those of adjacent upper strata known to be around 2 Ma. Walker et al. (2006) used U–Pb isochron dating on the flowstones immediately above and below the skeleton, and Pickering and Kramers (2010) dated the overlying flow to suggest an age of a little over 2.2 Ma. The U–Pb ages indicated that the paleomagnetic signals in the flowstones had recorded the older and younger Réunion Events (short shifts to normal polarity that were discovered in lava from the island of Réunion), which means that the Little Foot age is between 2.4 and 2.2 Ma (Figure 6). The stratigraphy around the skeletal remains has been questioned, but U–Pb analysis of the lowest flowstone should help to settle the question (Bruxelles et al., 2014). The dating of Little Foot and of "Mrs. Ples" from Sterkfontein, another representative of *A. africanus*, also at around 2.2 Ma by magnetic polarity, was an important milestone for the chronology of the South African hominin record; until then, the complex South African cave deposits had eluded a secure chronometric dating analysis, and the biochronology of fossil animal assemblages could only roughly indicate ages of around 2 Ma. Across the valley, Swartkrans Cave, which contained representatives of *Paranthropus robustus*, has yielded dates by U–Pb analysis of flowstones and cosmogenic dates of sediments of 2.19 ± 0.08 Ma and 1.80 ± 0.09 Ma (Gibbon et al., 2014) and has yielded to flowstone U–Th analysis with an upper age estimate of 110 ka for its Middle Stone Age (Sutton et al., 2009).

Similar U–Pb studies in other parts of Sterkfontein and in another australopithecine site at Makapansgat (the Limeworks) have not met with success due to low U content in the speleothems and, in the latter cave, open-system isotopic disturbance in the earlier flowstones. A combination of biochronological dating using known suid (pig) faunal successions and magnetic polarities of flowstones and carbonate-cemented silts indicate ages for the two sets of strata containing the Makapansgat australopithecine hominins, of 2.7 and 2.5 Ma (Warr et al., forthcoming), making this the oldest dated australopithecine site in South Africa. Malapa Cave has yielded fairly complete male and female skeletons of a somewhat younger hominin, dubbed *A. sediba*, from sediment lying above a flowstone. The U–Pb analyses from the flowstone and magnetic polarity of the sediments indicate an age between 1.78 and 2.0 Ma (Dirks et al., 2010; Pickering et al., 2011).

Variations in the relative abundance of isotopes of oxygen (^{18}O and ^{16}O) and of carbon (^{13}C and ^{12}C) in speleothems have been used to establish long continuous records that can serve as proxies for climate and vegetational changes, respectively. Schwarcz and Ford were again instrumental in pursuing the use of fluid inclusions in speleothems as a means to recover paleotemperatures. The number of such studies has mushroomed in the new millennium (see McDermott, 2004), though it has to be said that a reliable and easy method of yielding absolute paleotemperatures has proved elusive.

Nevertheless, very useful climate change proxies have been produced from long stalagmites, particularly from Israel, stretching back to before the last interglacial, MIS 5 (Marine Isotope Stage 5). The long-term work of Miryam Bar-Matthews and coworkers (1997) in their sampling of cave dripwater at Soreq Cave, a show cave located southwest of Jerusalem, established annual correspondence between stable oxygen isotope signatures of rain and the signature in the cave dripwater. That correlation allowed them to interpret isotope signatures from a number of speleothem records from this cave. Amos Frumkin et al. (1999) dated a speleothem by TIMS from Jerusalem West Cave that extended the Near East isotope records back to about 170 ka. Bar-Matthews et al. (1999) elucidated the precipitation records, tested the viability of using speleothem fluid inclusions for paleotemperature work, and analyzed 12 speleothems, with partial overlaps, from Soreq Cave to extend their record back to 60 ka. The original alpha-based dates were replaced by 53 TIMS dates. The O-isotope record showed a good match to the Marine Isotope Stage (MIS) records, including cold peaks in good agreement with the Greenland short ice-core events known as Heinrich events – H1 (16.5 ka), H2 (25 ka) and H5 (46 ka) – and the Younger Dryas between 13.2 and 11.4 ka. In Bar-Matthews et al. (2000), further analyses of the Soreq speleothems appeared to show that four of five low $\delta^{18}O$ events spanning 140 ka corresponded well to organic marine mud (sapropel) horizons in Eastern Mediterranean marine cores and that they were due to enhanced annual precipitation, especially for the intervals 124–119 ka and 8.5–7.9 ka. Speleothems dated to between 90,000 and 53,000 years ago from Pinnacle Point Cave on South Africa's Cape coast demonstrated the correspondences between precipitation and vegetation type, and afforded comparison with the changes in regional lithic cultures and hence, of human ecology (Bar-Matthews et al., 2010). It appears that "Early modern humans in this region confronted a variable climate and adapted quickly in a manner similar to behaviorally modern humans" (Bar-Matthews et al., 2010, 2131).

A long O-isotope record was produced by Hopley et al. (2007) from a very uniformly deposited 2.3 m flowstone from the early Pleistocene Buffalo Cave, Makapansgat, South Africa. A combination of biochronology and reversal stratigraphy indicated an early Pleistocene age between 2 and 1 Ma. Astronomical dating, which uses the known phases of the orbital parameters of the Earth's orbit (ellipticity, 100 kyr; obliquity of the axis, 40 kyr; and precession of the axis, 21 kyr) was then used to fix the record to a period between 1.9 and 1.52 Ma. The carbon isotope part of the record showed that there had been a change in the type of plants using different photosynthetic pathways, known as C_3 and C_4 plants. The emergence of C_4 plants began in the tropics only in the Middle Miocene (20–15 Ma), and was an evolutionary response to cooler, drier climates and decreasing atmospheric CO_2 levels. The old 4 Ma flowstones at the Limeworks, Makapansgat, showed that C_4-type grasses had not yet reached that latitude (15° S) but that they were present by 1.9 Ma. The Buffalo Cave flowstone record shows that they increased in stepwise fashion, most prominently between 1.7 and 1.6 Ma. This was taken to suggest an increase in aridity at these latitudes that favored C_4 over C_3. The changing ecology was represented by an increase in Savannah, which might have contributed to the emergence of new hominins such as *Homo ergaster* and *H. erectus*, both having a body plan better suited to more open environments than had their precursor australopithecines.

Bibliography

Barkai, R., Gopher, A., Lauritzen, S. E., and Frumkin, A., 2003. Uranium series dates from Qesem Cave, Israel, and the end of the lower Palaeolithic. *Nature*, **423**(6943), 977–979.

Bar-Matthews, M., Ayalon, A., and Kaufman, A., 1997. Late Quaternary paleoclimate in the Eastern Mediterranean region from stable isotope analysis of speleothems at Soreq Cave, Israel. *Quaternary Research*, **47**(2), 155–168.

Bar-Matthews, M., Ayalon, A., Kaufman, A., and Wasserburg, G. J., 1999. The Eastern Mediterranean, paleoclimate as a reflection of regional events: Soreq cave, Israel. *Earth and Planetary Science Letters*, **166**(1–2), 85–95.

Bar-Matthews, M., Ayalon, A., and Kaufman, A., 2000. Timing and hydrological conditions of sapropel events in the Eastern Mediterranean, as evident from speleothems, Soreq Cave, Israel. *Chemical Geology*, **169**(1–2), 145–156.

Bar-Matthews, M., Marean, C. W., Jacobs, Z., Karkanas, P., Fisher, E. C., Herries, A. I. R., Brown, K., Williams, H. M., Bernatchez, J., Ayalon, A., and Nilssen, P. J., 2010. A high resolution and continuous isotopic speleothem record of paleoclimate and paleoenvironment from 90 to 53 ka from Pinnacle Point on the south coast of South Africa. *Quaternary Science Reviews*, **29** (17–18), 2131–2145.

Bischoff, J. L., Soler, N., Maroto, J., and Julià, R., 1989. Abrupt Mousterian/ Aurignacian boundary at c. 40 ka bp: Accelerator ^{14}C dates from l'Arbreda Cave (Catalunya, Spain). *Journal of Archaeological Science*, **16**(6), 563–576.

Bischoff, J. L., Garcia, J. F., and Straus, L. G., 1992. Uranium-series isochron dating at El Castillo cave (Cantabria, Spain): the "Acheulian"/"Mousterian" question. *Journal of Archaeological Science*, **19**(1), 49–62.

Bischoff, J. L., Ludwig, K., Garcia, J. F., Carbonell, E., Vaquero, M., Stafford, T. W., Jr., and Jull, A. J. T., 1994. Dating of the basal Aurignacian sandwich at Abric Romaní (Catalunya, Spain) by radiocarbon and uranium-series. *Journal of Archaeological Science*, **21**(4), 541–551.

Bischoff, J. L., Shamp, D. D., Aramburu, A., Arsuaga, J. L., Carbonell, E., and Bermudez de Castro, J. M., 2003. The Sima de los Huesos hominids date to beyond U/Th equilibrium (>350 kyr) and perhaps to 400–500 kyr: new radiometric dates. *Journal of Archaeological Science*, **30**(3), 275–280.

Bischoff, J. L., Williams, R. W., Rosenbauer, R. J., Aramburu, A., Arsuaga, J. L., García, N., and Cuenca-Bescós, G. L., 2007. High-resolution U-series dates from the Sima de los Huesos hominids yields 600+∞/–66 kyrs: implications for the evolution of the early Neanderthal lineage. *Journal of Archaeological Science*, **34**(5), 763–770.

Blackwell, B., Schwarcz, H. P., and Debénath, A., 1983. Absolute dating of hominids and Palaeolithic artifacts of the cave of La Chaise-de-Vouthon (Charente), France. *Journal of Archaeological Science*, **10**(6), 493–513.

Bourdon, B., Henderson, G. M., Lundstrom, C. C., and Turner, S. (eds.), 2003. *Uranium-Series Geochemistry*. Washington, DC/St. Louis: Geochemical Society and Mineralogical Society of America. Reviews in Mineralogy and Geochemistry, Vol. 52.

Bruxelles, L., Clarke, R. J., Maire, R., Ortega, R., and Stratford, D., 2014. Stratigraphic analysis of the Sterkfontein StW 573 *Australopithecus* skeleton and implications for its age. *Journal of Human Evolution*, **70**, 36–48.

Cliff, R. A., Spötl, C., and Mangini, A., 2010. U–Pb dating of speleothems from spannagel cave, Austrian alps: a high resolution comparison with U-series ages. *Quaternary Geology*, **5**(4), 452–458.

Dirks, P. H. G. M., Kibii, J. M., Kuhn, B. F., Steininger, C., Churchill, S. E., Kramers, J. D., Pickering, R., Farber, D. L., Mériaux, A.-S., Herries, A. I. R., King, G. C. P., and Berger, L. R., 2010. Geological setting and age of *Australopithecus sediba* from Southern Africa. *Science*, **328**(5975), 205–208.

Falguères, C., de Lumley, H., and Bischoff, J. L., 1992. U-series dates for stalagmitic flowstone E (Riss/Würm interglaciation) at Grotte du Lazaret, Nice. *Quaternary Geology*, **38**(2), 227–233.

Falguères, C., Yokoyama, Y., Shen, G., Bischoff, J. L., Ku, T.-L., and de Lumley, H., 2004. New U-series dates at the Caune de l'Arago, France. *Journal of Archaeological Science*, **31**(7), 941–952.

Ford, D. C., and Williams, P. W., 2007. *Karst Geomorphology and Hydrology*. London: Wiley. rev. edition.

Frumkin, A., Ford, D. C., and Schwarcz, H. P., 1999. Continental oxygen isotopic record of the last 170,000 years in Jerusalem. *Quaternary Research*, **51**(3), 317–327.

Gibbon, R. J., Pickering, T. R., Sutton, M. B., Heaton, J. L., Kuman, K., Clarke, R. J., Brain, C. K., and Granger, D. E., 2014. Cosmogenic nuclide burial dating of hominin-bearing Pleistocene cave deposits at Swartkrans, South Africa. *Quaternary Geochronology*, **24**, 10–15.

Gradstein, F. M., Ogg, J. G., Schmitz, M. D., and Ogg, G. M., 2012. *The Geologic Timescale 2012*. Amsterdam: Elsevier.

Granger, D. E., and Muzikar, P. F., 2001. Dating sediment burial with in situ-produced cosmogenic nuclides: theory, techniques, and limitations. *Earth and Planetary Science Letters*, **188** (1–2), 269–281.

Green, H. S., Stringer, C. B., Collcutt, S. N., Currant, A. P., Huxtable, J., Schwarcz, H. P., Debenham, N., Embleton, C., Bull, P., Molleson, T. I., and Bevins, R. E., 1981. Pontnewydd cave in Wales – a new middle Pleistocene hominid site. *Nature*, **294**(5843), 707–713.

Hill, C. A., and Forti, P., 1997. *Cave Minerals of the World*, 2nd edn. Huntsville: National Speleological Society.

Hopley, P. J., Weedon, G. P., Marshall, J. D., Herries, A. I. R., Latham, A. G., and Kuykendall, K. L., 2007. High- and low-latitude orbital forcing of early hominin habitats in South Africa. *Earth and Planetary Science Letters*, **256**(3–4), 419–432.

Ivanovich, M., and Harmon, R. S. (eds.), 1992. *Uranium-Series Disequilibrium. Applications to Earth, Marine, and Environmental Sciences*, 2nd edn. Oxford: Oxford University Press.

Latham, A. G., and Ford, D. C., 1993. The paleomagnetism and rock magnetism of cave and karst deposits. In Aïssaoui, D. M., McNeill, D. F., and Hurley, N. F. (eds.), *Applications of Paleomagnetism to Sedimentary Geology*. Tulsa: Society for Sedimentary Geology. Society of Economic Paleontologists and Mineralogists Special Publication, Vol. 49, pp. 150–155.

Latham, A. G., and Schwarcz, H. P., 1992. The petralona hominid site: uranium-series re-analysis of 'Layer 10' calcite and associated palaeomagnetic analyses. *Archaeometry*, **34**(1), 135–140.

Latham, A. G., Schwarcz, H. P., Ford, D. C., and Pearce, G. W., 1979. Palaeomagnetism of stalagmite deposits. *Nature*, **280**(5721), 383–385.

Lundberg, J., and McFarlane, D. A., 2007. Pleistocene depositional history in a periglacial terrane: a 500 k.y. Record from kents cavern, Devon, United Kingdom. *Geosphere*, **3**(4), 199–219.

McDermott, F., 2004. Palaeo-climate reconstruction from stable isotope variations in speleothems: a review. *Quaternary Science Reviews*, **23**(7–8), 901–918.

McFarlane, D. A., and Lundberg, J., 2005. The 19th century excavation of Kent's Cavern, England. *Journal Caveand Karst Studies*, **67**(1), 39–47.

Partridge, T. C., Granger, D. E., Caffee, M. W., and Clarke, R. J., 2003. Lower Pliocene hominid remains from Sterkfontein. *Science*, **300**(5619), 607–612.

Pickering, R., and Kramers, J. D., 2010. Re-appraisal of the stratigraphy and determination of new U–Pb dates for the Sterkfontein hominin site, South Africa. *Journal of Human Evolution*, **59**(1), 70–86.

Pickering, R., Dirks, P. H. G. M., Jinnah, Z., de Ruiter, D. J., Churchill, S. E., Herries, A. I. R., Woodhead, J. D., Hellstrom, J. C., and Berger, L. R., 2011. *Australopithecus sediba* at 1.977 Ma and implications for the origins of the genus *Homo*. *Science*, **333**(6048), 1421–1423.

Pike, A. W. G., Hoffmann, D. L., García-Diez, M., Pettitt, P. B., Alcolea, J., De Balbín, R., González-Sainz, C., de las Heras, C., Lasheras, J. A., Montes, R., and Zilhão, J., 2012. U-series dating of Paleolithic art in 11 caves in Spain. *Science*, **336**(6087), 1409–1413.

Schwarcz, H. P., and Latham, A. G., 1984. Uranium-series age determination of travertines from the site of Vértesszöllös, Hungary. *Journal of Archaeological Science*, **11**(4), 327–336.

Schwarcz, H. P., and Latham, A. G., 1989. Dirty calcites I: uranium-series dating of contaminated calcite using leachates alone. *Chemical Geology Isotope Geoscience Section*, **80**(1), 35–43.

Schwarcz, H. P., and Skoflek, I., 1982. New dates for the Tata, Hungary archaeological site. *Nature*, **295**(5850), 590–591.

Schwarcz, H. P., Grün, R., Latham, A. G., Mania, D., and Brunnacker, K., 1988. The Bilzingsleben archaeological site: new dating evidence. *Archaeometry*, **30**(1), 5–17.

Sutton, M. B., Pickering, T. R., Pickering, R., Brain, C. K., Clarke, R. J., Heaton, J. L., and Kuman, K., 2009. Newly discovered fossil- and artifact-bearing deposits, uranium-series ages, and

Plio-Pleistocene hominids at Swartkrans Cave, South Africa. *Journal of Human Evolution*, **57**(6), 688–696.

Walker, J., Cliff, R. A., and Latham, A. G., 2006. U–Pb isotopic age of the StW 573 hominid from Sterkfontein, South Africa. *Science*, **314**(5805), 1592–1594.

Warr, G. L., Herries, A. I. R., Cliff, R. A., and Latham, A. G., forthcoming. Age estimates for the australopithecine fossils at Makapansgat, Limpopo Province, South Africa. *Journal of Human Evolution*.

Weninger, B., and Jöris, O., 2008. A ^{14}C age calibration curve for the last 60 ka: the Greenland-Hulu U/Th timescale and its impact on understanding the Middle to Upper Paleolithic transition in Western Eurasia. *Journal of Human Evolution*, **55**(5), 772–781.

Cross-references

Atapuerca
Cave Settings
Cosmogenic Isotopic Dating
Electron Spin Resonance (ESR) in Archaeological Context
Inductively Coupled Plasma-Mass Spectrometry (ICP-MS)
Isochron Dating
Kebara Cave
Mount Carmel
Oxygen Isotopes
Paleomagnetism
Pinnacle Point
Radiocarbon Dating
Spring Settings
Stable Carbon Isotopes in Soils
Sterkfontein/Swartkrans/Kromdraai
U-Series Dating

SPRING SETTINGS

Gail M. Ashley
Department of Earth and Planetary Sciences, Rutgers University, Piscataway, NJ, USA

Synonyms

Groundwater discharge

Definitions

Spring: a localized discharge of groundwater disgorging from a point source.

Seep: multisource discharge of groundwater as a "spring line" or a broad, diffuse wet area.

Spring-fed river: a drainage way that may contain perennial flow sourced by groundwater despite a negative hydrologic budget.

Spring-fed wetland: an area sourced by groundwater that comprises perennially damp ground and/or standing, shallow water supporting aquatic vegetation.

Aquifer: a geologic formation that contains sufficient saturated permeable material to yield significant quantities of water to springs or wells.

Springs

Geology of springs

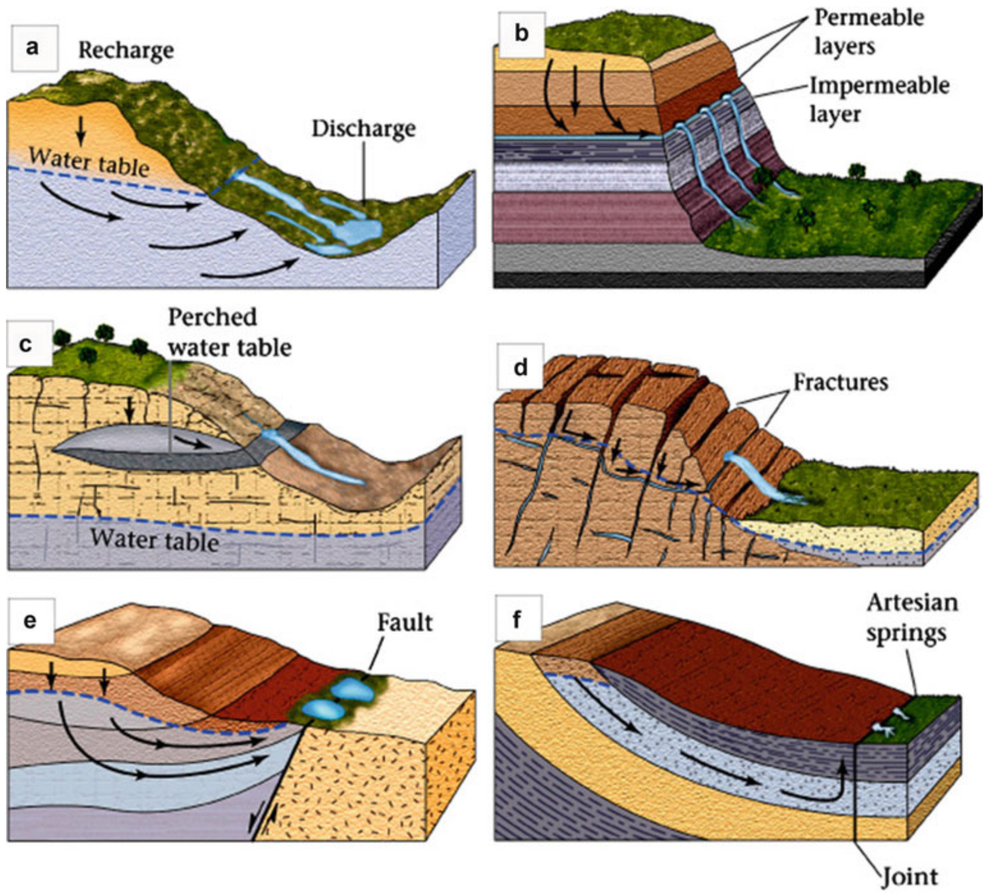
A spring is a localized discharge of groundwater disgorging onto the Earth's surface. The source of the groundwater may be a great distance (tens to hundreds of kilometers) away, and the water may move at a slow rate (meters/year). There are varied natural geologic settings that result in groundwater flowing onto the surface, thereby creating springs and seeps (Bryan, 1919; Fetter, 2001). Common examples include the intersection of the water table – i.e., top of the groundwater – with the land surface (Figure 1a), or when water percolating from the surface meets an impervious layer (Figure 1b). Other examples include a perched water table caused by the local interruption of water percolating downward (Figure 1c) or water moving through, and out of, a set of fractures (Figure 1d). Artesian flow (confined groundwater) may discharge from a fault (Figure 1e) or a joint, i.e., a single fracture with no evidence of movement between adjacent blocks (Figure 1f) (Marshak, 2001). These fractures provide a conduit to the surface for water flowing under hydrostatic head (pressure) (Figure 1e, f). In geologically complex areas, the groundwater is likely to be multisourced, and the location of groundwater discharge can vary temporally due to climate change or tectonic activity that creates faults or changes the gradient of the land (Rosen, 1994).

Hydrology of springs

The ultimate source of freshwater for any region is precipitation (P), but the net amount of water in the system annually depends on additional factors, such as evaporation (E) and type of vegetation present (both strongly influenced by temperature). Temperature is in turn a function of latitude and elevation of the location. Plants utilize some water and return it to the atmosphere by evaporation and plant transpiration (T), or evapotranspiration (ET). The rest of the precipitation enters the surface and groundwater system. The position of the groundwater table fluctuates with short-term and long-term changes in the regional hydrologic budget. $P > E + ET$ would represent a positive budget; $P < E + ET$ would reflect a negative budget. The water table rises when there is a sustained positive budget, and it falls when there is a sustained negative budget. Groundwater flow velocity is slow (meters/year), so there would likely be a lag in time between changes in amount of rainfall and the resulting increase or decrease in the volume of water in the ground. As many factors affect the volume of groundwater, the regional water table can be found anywhere between essentially the Earth's surface to hundreds of meters below the surface.

Water quality of springs

The composition of spring water varies considerably, reflecting the history of the water, including its source, rocks along the flow path, flow rate, etc.



Spring Settings, Figure 1 Geological settings of springs: (**a**) groundwater table intersects the surface; (**b**) water percolating down from the surface intercepts an impermeable layer; (**c**) water percolating from the surface intercepts a localized impermeable layer creating a perched water table; (**d**) in areas of dense bedrock, groundwater typically follows fractures, which act as preferred pathways for flow; (**e**) groundwater moves along fault planes, which act as a conduit for flow to the surface; (**f**) example of artesian flow (water enters the ground at higher elevation and exits upward along joint fractures under pressure) (Modified from Marshak (2001)).

The physiochemical environment, which includes the pH, temperature, and levels of oxygen and carbon dioxide, affects the productivity, abundance, and diversity of plants, microbes, and invertebrates. On the other hand, the biotic component, particularly vegetation, can affect spring hydrology by blocking drainage and retarding runoff. In areas of high heat flow, water in hot springs may reach 100 °C and is typically alkaline (pH = 8−10). Water may be salty if contaminated by surface brines or evaporites at depth. Erupting spring water may reach super saturation of carbonate as CO_2 is degassed when it flows onto the surface; pH tends to rise as degassing occurs, thereby reducing carbonate solubility and causing the precipitation of carbonate deposits near the spring orifice (Figure 2). Blue-green algae, bacteria, and cyanobacteria are the most common microbial forms associated with the precipitation of carbonate and siliceous minerals (Chafetz and Folk, 1984; Jones and Renaut, 1998).

Spring Settings, Figure 2 Photograph of a carbonate deposit (tufa) precipitated at a spring about 1.75 Ma in Lowermost Bed II, Olduvai Gorge, Tanzania. Oldowan stone tools were found in equivalent age strata. Geology hammer (30 cm) gives the scale.

Associated spring-fed environments

Although freshwater springs and seeps may be an attraction for animals and people, it is unlikely that archaeological sites would be found directly at the spring itself. In fact, there are very few examples of archaeological materials occurring in spring deposits, e.g., Florisbad, South Africa (Grün et al., 1996). The inherent dangers associated with the water source, such as carnivores seeking prey (Domínguez-Rodrigo et al., 2007), the possibility of encountering thirsty or frightened animals, and the potential for conflicts with other humans would result in short visits. Archaeological sites interpreted to be linked to springs are usually located a distance away (tens to a few hundred meters) in environments that are associated with groundwater discharge, such as a river bed (Ashley et al., 2011) or floodplain and groundwater-fed wetlands (Ashley, 2001; Ashley et al., 2009).

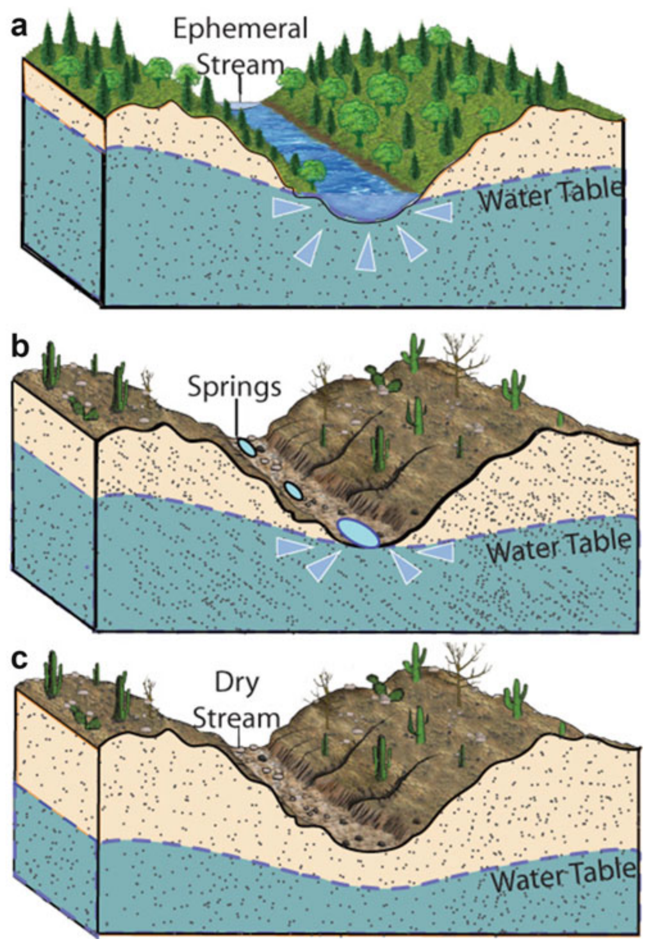
Rivers

Rivers are traditionally considered to be part of the surface water system that conveys discharge within channels from higher elevations of a watershed to lower elevations, where the water finally flows into an interior basin or into the ocean. But, rivers are not separate and distinct from the groundwater system; the two systems are, in fact, interrelated (Figure 3). For example, under wetter conditions, groundwater seeps into the river through channel boundaries (Figure 3a), augmenting water already in the river channel (i.e., increasing groundwater inflow creates a "gaining stream"). If conditions become drier, the river level drops as river water percolates downward, leaving a nearly dry riverbed. Water may completely disappear except for localized pools in the deeper parts of the river channel that are sustained by the uppermost parts of the groundwater flow (Figure 3b). When pools are spring fed, they may persist during even the driest time of the year if the water source is an aquifer being recharged at a distal location. The aquifer would also be protected from evaporation and utilization by vegetation. Under even drier conditions (Figure 3c), the water table would drop further (i.e., creating a "losing stream" where the river channel is located higher than the groundwater). If rainfall or a flash flood occurred in the area, water would soak into the ground until it reached the water table.

Wetlands

The water flowing from springs or seeps and from diffuse areas of groundwater discharge commonly results in freshwater wetlands (marshes, wet meadows, and groundwater forests) that may cover large expanses of landscape (Figure 4). These groundwater-fed sources tend to be persistent, as groundwater reservoirs are less vulnerable to fluctuations in precipitation and evaporation than are surface reservoirs (Liutkus and Ashley, 2003; Johnson et al., 2009; Ashley et al., 2010b). Wetlands can occur in any setting where the water table is near or at the surface. Ephemeral wetlands are linked to seasonal rainy periods or a perched water table (Figure 1c), whereas perennial wetlands occur in settings with a more permanent water source. They are often found at the interface of terrestrial ecosystems (such as upland forests and grasslands) and aquatic ecosystems (such as lakes and rivers), and thus they are often overlooked as part of a natural continuum (Mitsch and Gosselink, 2000).

The geomorphology of a spring and wetland complex is typically low relief and comprises a labyrinth of waterways of open water fringed with peats rooted on slightly higher ground. On increasingly higher terrain, the vegetation changes from marsh to wet meadow to groundwater forest characterized by a succession of plants with a decreasing tolerance for standing water



Spring Settings, Figure 3 Groundwater and surface water (rivers) are interactive systems: (**a**) groundwater enters the river through the sides and bottom of channel creating a "gaining stream"; (**b**) groundwater table is just below the channel bottom but supports springs in low-lying places within an otherwise dry stream bed; (**c**) a "losing stream" occurs where water percolates downward to a subsurface water table and is not accessible from the surface (Modified from Marshak (2001)).

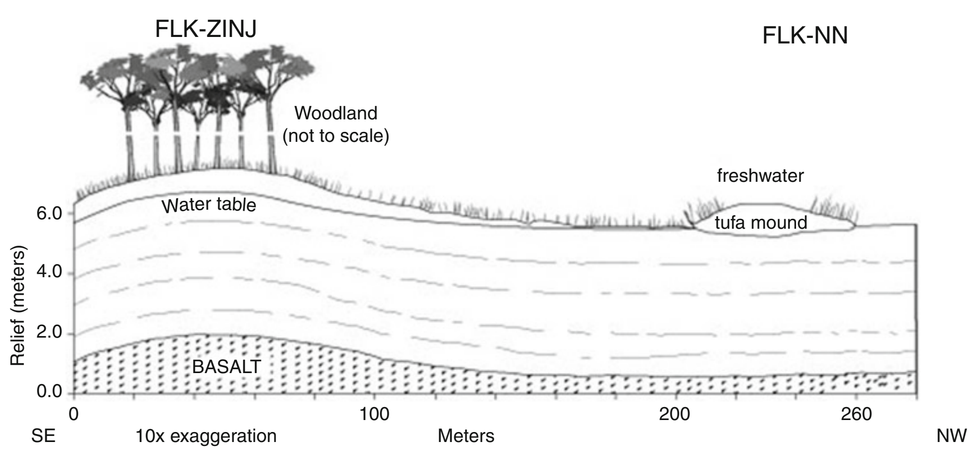
(Mitsch and Gosselink, 2000). Lush wetland vegetation and mineral licks attract grazing and browsing animals, providing hunting and scavenging opportunities for humans (Haynes and Agogino, 1966). Wet ground and marshes were likely used to trap animals for easy slaughter. Groundwater forests offered sources of fruits and vegetables and safe sleeping localities for our human ancestors. Wetland plants such as cattail (*Typha* spp.) and reeds (*Phragmites* spp.) were widely used for food, medicine, textiles, and building materials (Nicholas, 1998). In addition, thermal springs may have had medicinal or therapeutic uses (Griffin and Sattler, 1988).

Although groundwater discharge areas are well known in modern times as water sources for animals, particularly in arid settings (Behrensmeyer, 1978), their presence in the geological record has been recognized only recently (Quade et al., 1995; Ashley, 2000; Deocampo et al., 2002; Smith et al., 2004; Ashley et al., 2009; Ashley et al., 2010a). The bulk of the sediment record is generally silt and clay-sized material: 50–60 % clay, 20–30 % organic matter, and 10–20 % silt. The mineralogy of the clay provides a record of the water quality and is thus useful in paleoenvironmental interpretation. Clay minerals such as smectite and sepiolite indicate freshwater and lower pH; potassium feldspar and illite form in more alkaline-saline conditions (Hay et al., 1986).

Spring Settings, Figure 4 Photograph of a groundwater-fed wetland in the foreground and groundwater-fed forest in the distance. Ngorongoro Crater, Tanzania.

Case study: archaeological site at Olduvai Gorge, Tanzania

Mary and Louis Leakey discovered the hominin fossil *Zinjanthropus boisei* – referred to as "Zinj" and later renamed *Paranthropus boisei* (Leakey, 1971) – in Olduvai Gorge, Tanzania in 1959. Excavations of the surrounding area (~315 m^2) recovered ~2,500 Oldowan stone artifacts and 3,500 fossil bone specimens, including remains of another species, *Homo habilis*. The site (FLK Zinj) is recognized as one of the best co-occurrences of localized, high-density Oldowan tools and fossilized bones in East Africa, but why this unique archaeological site occurred at this specific location in the Olduvai Basin was a mystery for several decades. There were no rivers, and the nearby lake was salty. In 2008, a paleolake was identified, based on a thick carbonate tufa deposit at the site of FLK NN, 200 m from the Zinj fossil locality (Figure 5). The Zinj site itself was situated within a thick woodland, based upon plant remains (pollen and phytoliths) in the sediment associated with the bones and stone tools (Ashley et al., 2010a). The mystery was thereby solved; the most likely reason for the archaeological site being in a wooded locality is that the trees and underbrush provided temporary safety for hominins that were scavenging carnivore kills or perhaps even hunting



Spring Settings, Figure 5 Diagram showing the location of the archaeological site (FLK Zinj) in a woodland about 200 m from a freshwater spring (FLK NN).

animals attracted to the spring. It appears that carcasses were carried to the woodland by hominins for safe consumption.

Summary and conclusions

Springs and archaeology

Potable water sources are foci of human activity, and thus, temporary, seasonal, and permanent occupation sites are commonly associated with them. The inherent dangers of encounters with animals and other humans make it unlikely for such occupations to be established immediately adjacent to a spring or seep, but instead they tend to be located at a discreet distance. Archaeological sites are also commonly found associated with, but at safe distances from, freshwater sources, and many are in areas that have excellent preservation potential. Riverbanks, floodplains, and deltas or margins of permanent water bodies ranging from large lakes to small ponds have long been recognized as areas used by humans. Frequent changes in the water level of rivers and lakes typically include transgressions that cover occupation sites with a blanket of organic-rich sediment that slows the weathering process and helps preserve the archaeological record, as well as associated organic material such as bones and plant remains (Deocampo et al., 2002), and structures such as footprints, burrows, or fire pits (Ashley and Liutkus, 2003).

Springs themselves are usually small in area and may not always leave a mineral record. Therefore, identifying the records of associated groundwater-fed environments, such as rivers and wetlands, is important in interpreting the paleolandscape of the site.

Archaeological sites representing permanent or semi-permanent occupation associated with riverbed springs are likely to be on floodplains or higher terraces (Wright et al., 2007), but some material that has not been fluvially transported may be left on the riverbed itself and later buried (Ashley et al., 2011). The field of wetland archaeology has a long history and a number of excellent records (Coles, 1984; Coles and Coles, 1989; Bernick, 1998; Purdy, 2001). The reducing conditions in wetlands are conducive to the preservation of biological remains and also limit weathering of bones and artifacts.

The nature and longevity of spring environments and their attraction for people and animals is a direct function of the hydrologic budget. The appearances and disappearances of groundwater-fed systems on the landscape in a particular geologic setting vary with climate. These systems occur under both arid and humid environments but would be particularly important in arid regions as a dependable source of water during short- and long-term droughts.

Bibliography

Ashley, G. M., 2000. Geologists probe hominid environments. *GSA Today*, **10**(2), 24–29.

Ashley, G. M., 2001. Archaeological sediments in springs and wetlands. In Stein, J. K., and Farrand, W. R. (eds.), *Sediments in Archaeological Contexts*. Salt Lake City: University of Utah Press, pp. 183–210.

Ashley, G. M., and Liutkus, C. M., 2003. Tracks, trails and trampling by large vertebrates in a rift valley paleo-wetland, lowermost Bed II, Olduvai Gorge, Tanzania. *Ichnos*, **9**(1–2), 23–32.

Ashley, G. M., Tactikos, J. C., and Owen, R. B., 2009. Hominin use of springs and wetlands: Paleoclimate and archaeological records from Olduvai Gorge (~1.79–1.74 Ma). *Palaeogeography Palaeoclimatology Palaeoecology*, **272** (1–2), 1–16.

Ashley, G. M., Barboni, D., Domínguez-Rodrigo, M., Bunn, H. T., Mabulla, A. Z. P., Diez-Martín, F., Barba, R., and Baquedano, E., 2010a. A spring and wooded habitat at FLK Zinj and their relevance to origins of human behavior. *Quaternary Research*, **74**(3), 304–314.

Ashley, G. M., Domínguez-Rodrigo, M., Bunn, H. T., Mabulla, A. Z. P., and Baquedano, E., 2010b. Sedimentary geology and human origins: a fresh look at Olduvai Gorge, Tanzania. *Sedimentary Research*, **80**(8), 703–709.

Ashley, G. M., Ndiema, E. K., Spencer, J. Q. G., Harris, J. W. K., and Kiura, P. W., 2011. Paleoenvironmental context of archaeological sites, implications for subsistence strategies under Holocene climate change, northern Kenya. *Geoarchaeology*, **26**(6), 809–837.

Behrensmeyer, A. K., 1978. Taphonomic and ecologic information from bone weathering. *Paleobiology*, **4**(2), 150–162.

Bernick, K. N., 1998. *Hidden Dimensions: The Cultural Significance of Wetland Archaeology*. Vancouver: University of British Columbia Press.

Bryan, K., 1919. Classification of springs. *Journal of Geology*, **27**(7), 522–561.

Chafetz, H. S., and Folk, R. L., 1984. Travertines: depositional morphology and the bacterially constructed constituents. *Journal of Sedimentary Petrology*, **54**(1), 289–316.

Coles, J. M., 1984. *The Archaeology of Wetlands*. Edinburgh: Edinburgh University Press.

Coles, B., and Coles, J. M., 1989. *People of the Wetlands: Bogs, Bodies, and Lake Dwellers*. New York: Thames and Hudson.

Deocampo, D. M., Blumenschine, R. J., and Ashley, G. M., 2002. Wetland diagenesis and traces of early hominids, Olduvai Gorge, Tanzania. *Quaternary Research*, **57**(2), 271–281.

Domínguez-Rodrigo, M., Barba, R., and Egelund, C. P., 2007. *Deconstructing Olduvai: A Taphonomic Study of the Bed I Sites*. Dordrecht: Springer. Vertebrate Paleobiology and Paleoanthropology Series.

Fetter, C. W., 2001. *Applied Hydrogeology*, 4th edn. Englewood Cliffs: Prentice Hall.

Griffin, D. G., and Sattler, R. A., 1988. Alaska's thermal springs: a review of their biological and cultural significance in the lifeways of Alaskan natives. *Journal of Northern Sciences*, **2**, 49–73.

Grün, R., Brink, J. S., Spooner, N. A., Taylor, L., Stringer, C. B., Franciscus, R. G., and Murray, A. S., 1996. Direct dating of Florisbad hominid. *Nature*, **382**(6591), 500–501.

Hay, R. L., Pexton, R. E., Teague, T. T., and Kyser, T. K., 1986. Spring-related carbonate rocks, Mg clays, and associated minerals in Pliocene deposits of the Amargosa Desert, Nevada and California. *Geological Society of America Bulletin*, **97**(12), 1488–1503.

Haynes, C. V., Jr., and Agogino, G. A., 1966. Prehistoric springs and geochronology of the Clovis Site, New Mexico. *American Antiquity*, **31**(6), 812–821.

Johnson, C. R., Ashley, G. M., De Wet, C. B., Dvoretsky, R., Park, L., Hover, V. C., Owen, R. B., and McBrearty, S., 2009. Tufa as

a record of perennial fresh water in a semi-arid rift basin, Kapthurin Formation, Kenya. *Sedimentology*, **56**(4), 1115–1137.
Jones, B., and Renaut, R. W., 1998. Origin of platy calcite crystals in hot-spring deposits in the Kenyan Rift valley. *Journal of Sedimentary Research*, **68**(5), 913–927.
Leakey, M. D., 1971. *Olduvai Gorge: Excavations in Beds I and II, 1960–1963*. Cambridge: Cambridge University Press.
Liutkus, C. M., and Ashley, G. M., 2003. Facies model of a semiarid freshwater wetland, Olduvai Gorge, Tanzania. *Journal of Sedimentary Research*, **73**(5), 691–705.
Marshak, S., 2001. *Earth: Portrait of a Planet*. New York: W.W. Norton.
Mitsch, W. J., and Gosselink, J. G., 2000. *Wetlands*. New York: Wiley.
Nicholas, G. P., 1998. Wetlands and hunter-gatherers: a global perspective. *Current Anthropology*, **39**(5), 720–731.
Purdy, B. A., 2001. *Enduring Records: The Environmental and Cultural Heritage of Wetlands*. Oxford: Oxbow Press.
Quade, J., Mifflin, M. D., Pratt, W. L., McCoy, W., and Burckle, L., 1995. Fossil spring deposits in the southern Great Basin and their implications for changes in water-table levels near Yucca Mountain, Nevada, during Quaternary time. *Geological Society of America Bulletin*, **107**(2), 213–230.
Rosen, M. R., 1994. *Paleoclimate and Basin Evolution of Playa Systems*. Boulder: Geological Society of America. Geological Society of America, Special Paper 289.
Smith, J. R., Giegengack, R., Schwarcz, H. P., McDonald, M. M. A., Kleindienst, M. R., Hawkins, A. L., and Churcher, C. S., 2004. A reconstruction of Quaternary pluvial environments and human occupations using stratigraphy and geochronology of fossil-spring tufas, Kharga Oasis, Egypt. *Geoarchaeology*, **19**(5), 407–439.
Wright, D. K., Forman, S. L., Kusimba, C. M., Pierson, J., Gomez, J., and Tattersfield, P., 2007. Stratigraphic and geochronological context of human habitation along the Galana River, Kenya. *Geoarchaeology*, **22**(7), 709–728.

Cross-references

Alluvial Settings
Geomorphology
Paleoenvironmental Reconstruction
Paludal Settings (Wetland Archaeology)
Sedimentology
Site Formation Processes
Trampling

STABLE CARBON ISOTOPES IN SOILS

Lee C. Nordt[1] and Vance T. Holliday[2]
[1]Department of Geology, Baylor University, Waco, TX, USA
[2]Anthropology and Departments Geosciences, University of Arizona, Tucson, AZ, USA

Definition

Stable isotopes of carbon (^{13}C and ^{12}C) in soil organic matter and in pedogenic carbonate provide a means of paleoenvironmental reconstruction because the ratio of these two isotopes is influenced by biological, physical, and chemical reactions. The C_3 and C_4 plant communities that produced the organic carbon can be identified isotopically based on the degree of discrimination against atmospheric $^{13}CO_2$ during photosynthesis (the degree to which a plant favors carbon dioxide containing the lighter $^{12}CO_2$ isotope).

Introduction

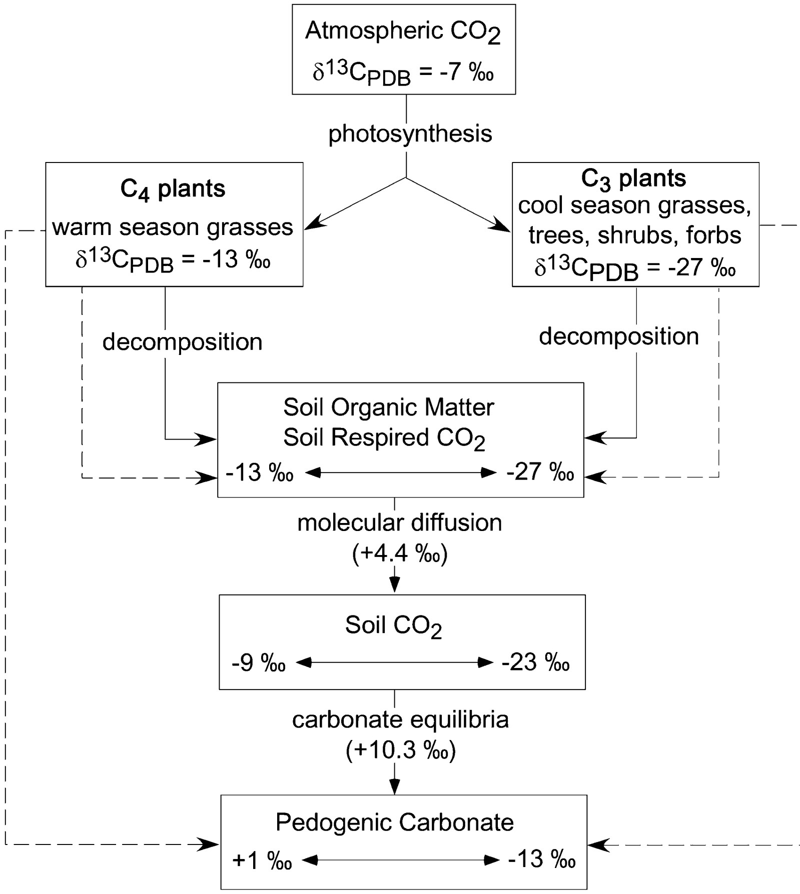
The distribution of stable C isotopes in surface and buried soils is a powerful indicator of many kinds of pedologic and paleoenvironmental interpretations. Stable C isotope analysis of soil organic matter is commonly employed to quantify organic matter turnover rates (Balesdent and Mariotti, 1996; Bernoux et al., 1998) and to reconstruct past vegetation communities (Cerling, 1992; Cerling et al., 1993; Kelly et al., 1993; Wang et al., 1993; Nordt et al., 1994; Boutton, 1996; Nordt et al., 1996, 2008; Fredlu,nd and Tieszen, 1997; Boutton et al., 1998; von Fischer et al., 2008; Hall and Penner, 2013). Stable C isotopes of pedogenic carbonate are used for quantifying rates of pedogenesis, estimating pathways of soil development, and inferring landscape age (Amundson et al., 1988; Marion et al., 1991; Nordt et al., 1996, 1998). As with soil organic matter, stable C isotopes of pedogenic carbonate can be employed as a proxy for paleoclimate reconstruction (Quade et al., 1989; Cerling and Quade, 1993; Cole and Monger, 1994; Humphrey and Ferring, 1994; Monger, 1995).

The primary application of stable C isotope analysis in soils to archaeological research is for paleoenvironmental reconstruction (Nordt, 2001). This method is particularly effective in semiarid to subhumid climates where plant communities have experienced changes in the ratio of C_3 to C_4 species or soil biomass production. These areas typically include tropical/temperate grasslands, semidesert and dry steppes, and tropical shrub/woodlands. Humid or tropical climates that have been continuously forested, or polar regions with cool season grasses, are less likely to have supported a C_4 plant community.

Theory and application of isotope pedology

Surface and buried soils store important paleoenvironmental information applicable to solving archaeological problems because pedogenesis is strongly influenced by climate and vegetation (Birkeland, 1999). Soils contain two components that can be analyzed isotopically for paleoenvironmental reconstruction: organic matter and pedogenic carbonate. Both of these materials contain carbon that is derived from decaying plant matter, which is the link between soil and vegetation/climate.

Organic matter consists mainly of decomposed plant litter in surface and near-surface layers (A or O horizons) that impart a dark color to the soil. Organic matter accumulates in the early stages of soil development until inputs and outputs become equal (steady state), typically within 1,000 years (Birkeland, 1999; Buol et al., 2011; Nordt et al., 2011). The amount of soil organic matter decreases



Stable Carbon Isotopes in Soils, Figure 1 Photosynthetic pathway for C_4 and C_3 plants and associated $\delta^{13}C_{PDB}$ values for soil organic matter, respired soil CO_2, and pedogenic carbonate. *Dashed lines* represent ways by which the proportion of C_4 and C_3 plants can be estimated knowing soil organic matter or pedogenic carbonate $\delta^{13}C_{PDB}$ values (Modified from Nordt, 2001: Figure 15.2).

with depth as biological activity decreases, whereas the whole soil amount of soil organic matter decreases in drier climates where plant biomass production is lower. In contrast, most pedogenic carbonate typically accumulates in lower soil layers (Bk horizons) at the terminus of a wetting front, due to CO_2 degassing and dewatering from evapotranspiration. These processes enrich the soil solution in calcium and bicarbonate ions to the point that a carbonate precipitate forms. Pedogenic carbonate typically accumulates as nodules, filaments, or indurated masses that are morphologically visible in the field and in a disseminated form that is only visible at the microscopic level. In nonleaching environments, and with an abundant source of calcium and carbonate ions, the accumulation of soil carbonate increases with time (Birkeland, 1999; Buol et al., 2011).

There are three carbon isotopes in nature: ^{14}C, ^{13}C, and ^{12}C (Hoefs, 1987). The ^{14}C isotope undergoes radioactive decay and is commonly used for radiocarbon dating of late Quaternary materials. The ^{12}C and ^{13}C isotopes are stable, and the ratio of these two isotopes is influenced by biological, physical, and chemical reactions. The amount of fractionation that occurs between ^{13}C and ^{12}C is measured as the relative deviation between a sample and standard and is expressed in $\delta^{13}C$ notation. Three plant groups can be identified isotopically based on the degree of discrimination against atmospheric $^{13}CO_2$ during photosynthesis (Boutton, 1991a). The C_3 plants discriminate most against atmospheric $^{13}CO_2$ and in normal conditions produce $\delta^{13}C$ values around –27 ‰ (Figure 1). Plants that discriminate much less against atmospheric $\delta^{13}CO_2$ are C_4, which produce $\delta^{13}C$ values near –13 ‰. The C_3 plants consist mainly of trees, shrubs, forbs, and cool season grasses, whereas C_4 plants consist mainly of warm season grasses. CAM plants (Crassulacean acid metabolism) most often have a photosynthetic pathway similar to C_4 plants. However, facultative CAM plants can generate values that span the entire spectrum of C_3 to C_4 photosynthesis.

Virtually no isotopic fractionation occurs during decomposition of plant litter and subsequent incorporation of organic by-products into the soil organic matter pool (Nadelhoffer and Fry, 1988; von Fischer et al., 2008). Thus, the $\delta^{13}C$ value of soil organic matter reflects the proportion of C_3 and C_4 plants contributing organic material to the soil (Figure 1). For example, a pure C_4 plant community would produce soil organic matter with a $\delta^{13}C$ value of approximately –13 ‰, and equal contributions of C_3 and C_4 plants would produce a $\delta^{13}C$ value of approximately –20 ‰. Some authors have discovered that the isotopic composition of plants has fluctuated during the late Quaternary by as much as 2 ‰ in response to changes to atmospheric CO_2 levels (Marino et al., 1992). This amount still does not obscure major shifts in biomass production as reflected in the $\delta^{13}C$ values.

Plants with C_3 photosynthesis may grow in all environmental settings throughout the world, making them difficult to use as a paleoclimatic indicator. Facultative CAM plants are also problematic because they may yield both C_3 and C_4 isotopic signatures. The contribution of C_4 plants to the soil organic matter pool, however, is a reliable proxy for paleoclimatic reconstruction because the abundance of C_4 species (Teeri and Stowe, 1976) and their biomass production (von Fischer et al., 2008) are strongly and positively related to environmental temperature. Therefore, the $\delta^{13}C$ of soil organic matter can be used to interpret past vegetation communities and, from that, provide for general interpretations about past environmental temperatures (Figure 1).

The following mass balance in Eq. 1 illustrates how the proportion of C_4 and C_3 contributions to the soil organic matter pool can be estimated knowing a bulk soil $\delta^{13}C$ value:

$$\delta^{13}C = \left(\delta^{13}C_{C4}\right)(x) + \left(\delta^{13}C_{C3}\right)(1-x) \qquad (1)$$

where $\delta^{13}C$ is the value of the whole sample, $\delta^{13}C_{C4}$ is the average $\delta^{13}C$ value of the C_4 components of the sample, x is the proportion of carbon from C_4 plant sources, $\delta^{13}C_{C3}$ is the average $\delta^{13}C$ value of the C_3 components of the sample, and 1–x is the proportion of carbon derived from C_3 plant sources. Some natural variation exists in the end member $\delta^{13}C$ values for C_3 and C_4 plants (generally ± 1 ‰). Consequently, it may be necessary to construct an isotopic mixing line unique to the area of investigation.

Nordt et al. (2007) developed a transfer function from bulk $\delta^{13}C$ to mean July temperature from soils in the Great Plains (USA), where increasing C_4 biomass contributions related positively to higher summer temperatures. By applying the temperature equation to a suite of buried soils, they showed quantitative evidence for a middle Holocene Altithermal, for example. Hall and Penner (2013) took this method a step further by developing a transfer function for estimating summer rainfall. They were able to establish a rainfall curve from a suite of buried Holocene soils in New Mexico. Nordt et al. (2008) developed a relative scale for estimating changing contributions of C_4 plants using a method that compared the isotopic difference by latitude between the nearest modern soil (surface) $\delta^{13}C$ value to nearby buried soils of different ages throughout the Holocene. They were able to identify isotopically the Younger Dryas (decreasing C_4), Altithermal and Medieval Warm Period (increasing C_4), and Little Ice Age (decreasing C_4) in the Great Plains.

Soil organic matter is converted to respired CO_2 by microbial respiration and does not isotopically fractionate when fluxing from the ground surface (Cerling et al., 1991). During the instantaneous flux of respired CO_2, the lighter $^{12}CO_2$ isotope migrates more rapidly to the surface by molecular diffusion, thus theoretically enriching the remaining soil CO_2 by 4.4 ‰ (Cerling et al., 1991; Amundson et al., 1998). This soil CO_2 component takes part in carbonate equilibria reactions, which leads to an additional 10.3 ‰ enrichment in $\delta^{13}C$ (at 20 °C) as the soil CO_2 is transferred to the solid pedogenic carbonate phase (Cerling et al., 1989). Although this reaction is temperature dependent, the influence on isotopic values is minor within the temperature range of most soils (1–1.5 ‰). Thus, the pedogenic carbonate component of most soils can in theory be isotopically estimated by adding approximately 14–15 ‰ to soil organic matter or respired CO_2 as shown by the equation (Nordt et al., 1998):

$$\delta^{13}C \text{ pedogenic carbonate} = \delta_{CaCO3-CO2}\left(\delta^{13}C \text{ SOM} + 1004.4\right) - 1000 \qquad (2)$$

where $\delta_{CaCO3-CO2}$ is the fractionation factor between pedogenic carbonate and soil CO_2 (1.0103, which calculates to 10.3 ‰) and SOM is soil organic matter. Cerling and Quade (1993) show, however, that ^{13}C-enriched atmospheric CO_2 can mix with biologically produced soil CO_2 in arid regions where biological activity is low. Generally, this is not a factor at the depth at which pedogenic carbonate precipitates in subhumid to humid environments nor below a depth of 50 cm in semiarid or arid climates. Computer modeling provides the best means of estimating the $\delta^{13}C$ of pedogenic carbonate in areas where atmospheric mixing is significant (Cerling, 1984; Quade et al., 1989; Nordt et al., 1998).

Pedogenic carbonate accumulates in disseminated forms, nodular forms, and as indurated layers (Birkeland, 1999; Buol et al., 2011). The $\delta^{13}C$ value of these forms, if not contaminated with lithogenic or detrital pedogenic carbonate, can be used as a paleoclimatic proxy (Cerling and Quade, 1993). This is done by subtracting approximately 14–15 ‰ (at 20 °C) from the $\delta^{13}C$ value of pedogenic carbonate to estimate the proportion of C_3 and C_4 plants contributing organic matter to the soil organic matter pool at the time of carbonate precipitation. For example, a $\delta^{13}C$ value of –20 ‰ obtained from a pedogenic carbonate nodule would indicate equal contributions from C_3 and C_4 plants to soil organic matter production during the time of carbonate formation.

Sources of soil organic carbon

There are two sources of soil organic matter that commonly occur in late Quaternary environments (Nordt et al., 1994). The first is detrital, which is the organic fraction transported with mineral particles in alluvium, colluvium, eolian, or even glacial deposits. For example, if the drainage basin of a stream or the source area of eolian sediment does not cross major climatic or vegetation boundaries, a detrital organic carbon source is desirable because it represents local conditions. On the other hand, detrital isotopic signatures from large drainage basins or from distant eolian sources probably represent an average of several climatic and vegetation zones and cannot be interpreted as one environmental condition. Generally, transported organic carbon originates from the most easily erodible materials in the drainage basin or area in question. This tends to be from upland topsoils or older alluvial topsoils that carry a modern organic carbon isotopic signal. Again, this organic component is desirable for interpreting paleoenvironmental conditions. Some organic carbon may be derived from bedrock, but this component is much more likely to contain low quantities of organic carbon and consequently have its signal suppressed by modern carbon sources. Detrital isotopic values are more likely to be encountered in subsoils (B horizons) where pedogenic organic inputs are lower.

The second source of soil organic matter is pedogenic. This source is clearly desirable for paleoenvironmental reconstruction because the isotopic values reflect the vegetation growing directly in the soil. Pedogenic isotopic signatures of organic matter will be more evident in surface horizons where they are superimposed on detrital signatures. Mixing of detrital and pedogenic sources should also provide favorable isotopic results if the detrital component was transported a relatively short distance.

The stable C isotope composition of organic matter in upper horizons of buried soils may provide a discrete view of the isotopic plant community present during soil formation. This will be true provided that appreciable erosion of the surface horizon did not occur during soil burial or that significant biological mixing did not occur after burial. If the soil developed in uplands from sediments that have never been buried, it becomes more problematic to interpret either surface or subsurface isotopic values because long-term surface exposure may average isotopic conditions from two or more climatic intervals. Surface soils no more than a few thousand years old may also exhibit problems similar to older upland soils, depending on the frequency of climatic shifts in a particular area. In this case, data are needed from younger surface soils that can help partition differing vegetation and climatic intervals preserved in older soils.

Sources of carbon from pedogenic carbonate

Samples for stable C isotope analysis of pedogenic carbonate must also be interpreted with caution. The most common problem occurs when carbonate nodules appear to be pedogenic but instead are (1) lithogenic; (2) pedogenic, but engulfing lithogenic components; (3) pedogenic, but detrital; or (4) produced in association with ground water. Fortunately, most limestone $\delta^{13}C$ values (~0 ‰) are greater than pedogenic carbonate values that form in equilibrium with organic matter produced from C_3 or mixed C_3/C_4 plant communities (Figure 1). Unfortunately, pedogenic carbonate produced in association with organic matter from a pure C_4 plant community will yield $\delta^{13}C$ values similar to limestone (Figure 1). This problem can sometimes be resolved by insuring that the $\delta^{13}C$ of coexisting soil organic matter and pedogenic carbonate isotopically differ by 14–15 ‰ as theoretically predicted for most soils – see Eq. 2. Another technique would be to use petrographic thin section analysis because, in many instances, pedogenic and lithogenic carbonates have different micromorphic attributes (West et al., 1988). One example of this situation is that carbonate formed as root casts normally indicates in situ pedogenesis. Pedogenic carbonate that is eroded and redeposited is also difficult to identify, but the depth of nodules should occur systematically with climate. For example, pedogenic carbonate nodules accumulate at greater depths in subhumid climates than arid climates, all else being equal.

Some carbonate nodules precipitate in equilibrium with ground waters supersaturated with calcium and carbonate ions. This would yield isotopic values that are not in equilibrium with biologically produced soil CO_2. The presence of iron depletion zones or oxidized root channels observed in the field or in petrographic thin section (Vepraskas, 1994) may indicate whether groundwater was associated with formation of the carbonate. Carbonates precipitating within a capillary fringe of a groundwater table, however, probably will not pose a problem because biologically produced CO_2 will take part in the reaction.

Soil-stratigraphic interpretations

Depending on the presence or absence of buried soils, the length and pathway of pedogenesis of the buried soils, and the presence or absence of erosional unconformities, it may be difficult to estimate the timing of organic and inorganic carbon inputs in soil-stratigraphic sections. For example, with cumulic formation where pedogenesis keeps pace with deposition, a combination of detrital and pedogenic organic carbon isotopic signatures will be observed. However, organic inputs from pedogenic sources should dominate the isotopic record and reflect local vegetation conditions at the time of soil formation. In contrast, stable isotope values contained within a rapidly aggrading deposit will reflect basin-wide organic inputs. Yet, another example is an alluvial terrace soil that formed for thousands of years that might contain a mixture of isotopic signatures reflecting differing climate conditions.

Similar problems emerge when interpreting the isotopic signature of pedogenic carbonate nodules. These features form in association with CO_2 produced from organic matter decomposition, but carbonate nodules may take even longer to form such that there may be isotopic disequilibrium between the two carbon sources.

From a soil-stratigraphic perspective, the stable C isotope record should be interpreted within the context of at least several pedological and geological factors: (1) erosion, which removes part of the isotopic record; (2) rapid deposition, which creates a record strongly influenced by basin-wide vegetation conditions and isotopic signatures; and (3) minimal deposition, leading to pedogenesis with local vegetation conditions and isotopic signatures.

Stable isotope laboratory procedures

Bulk soil samples can be collected for stable C isotope analysis on a horizon-by-horizon basis or in predetermined depth increments. Minimum sample size depends on laboratory preparation procedures and mass spectrometer characteristics (Boutton, 1991b; Midwood and Boutton, 1998). Most laboratories use 0.5–1.0 mg of carbon for a single isotopic analysis. To meet this requirement, a minimum of 500 mg of bulk soil with 1–3 % organic matter is typically needed. If the bulk sample contains carbonate, a larger sample will be necessary because removal of the carbonate during pretreatment may significantly reduce the sample size. If a radiocarbon age is desired from the same zone, the sample will be small enough that an AMS (accelerator mass spectrometer) assay will probably be required. It is important to avoid large roots and layers that have noticeable mixing of materials from different horizons. This could occur from erosion, biological mixing, or shrink-swell activity in the soil.

Pedogenic carbonate comes in many sizes and shapes. If the soil developed from noncalcareous parent material, then the carbonate in the bulk sample is probably pedogenic (disseminated) and suitable for stable C analysis for paleoenvironmental reconstruction. Many situations, however, warrant collecting carbonate nodules for isotopic analysis to reduce potential contamination from lithogenic sources. In either case, a minimum of 10 mg of pure carbonate is needed to meet the minimum requirement of 0.5–1.0 mg of carbon for isotopic analysis. In most cases, more will be needed to account for the impurities that occur in most nodules (Boutton, 1991b). Ideally, it would be better to analyze several nodules independently within a soil horizon to get a sense of the isotopic variability likely to be encountered in a particular study area. As discussed in the previous section, avoid sampling large carbonate nodules for isotopic analysis, or else analyze discrete zones within large nodules.

Procedures for soil organic matter

In preparation for $\delta^{13}C$ analysis of soil organic matter, laboratories remove carbonate carbon with HCl (Boutton, 1991b; Midwood and Boutton, 1998). The residue is then converted to CO_2 during dry combustion, typically with CuO. The CO_2 is analyzed for variations in ^{13}C and ^{12}C content with an isotope ratio mass spectrometer. The difference in abundance between ^{13}C and ^{12}C in a particular substance is most commonly reported in units of $\delta^{13}C$, which is the relative deviation of the $^{13}C/^{12}C$ ratio of the sample from a standard. The standard for soil organic matter and pedogenic carbonate is Pee Dee Belemnite (PDB) limestone that has an assigned $\delta^{13}C$ value of 0 ‰. The equation for $\delta^{13}C$ determination is

$$\delta^{13}C_{PDB}(‰) = [(Rsample/Rstandard) - 1] \times 10^3 \quad (3)$$

where $\delta^{13}C$ has units of parts per thousand (per mil or ‰) and R is the mass45/mass44 of sample or standard CO_2. Negative $\delta^{13}C$ values represent a depletion in ^{13}C relative to the standard and positive $\delta^{13}C$ values of enrichment relative to the standard.

Procedures for pedogenic carbonate

For $\delta^{13}C$ analysis, pedogenic carbonate is decomposed to CO_2 by reaction with H_3PO_4 (Boutton, 1991b). As with soil organic matter, isotope ratio mass spectrometers are used to determine the isotopic ratios of carbonate. The standard for $\delta^{13}C$ of pedogenic carbonate is also PDB, with results reported in units per mil.

Laboratory comparisons

The most reliable means of determining $\delta^{13}C$ values for paleoenvironmental reconstruction is by employing stable isotope geochemistry laboratories designed specifically for this task. The $\delta^{13}C$ values are also produced in association with ^{14}C ages generated in radiocarbon laboratories. This is done to correct the $^{14}C/^{12}C$ ratio of the radiocarbon sample for variations in ^{13}C content produced by living organisms during photosynthesis (Trumbore, 1996). If a subsample of the radiocarbon sample is analyzed using standards and procedures of a stable isotope geochemistry laboratory, the $\delta^{13}C$ results should be suitable for paleoenvironmental reconstruction. However, the user must be aware that high level precision and accuracy for the $\delta^{13}C$ correction is not necessary for correcting ^{14}C ages. For example, each per mil difference between the $\delta^{13}C$ value generated by ^{14}C dating and the stable isotope value to PDB accounts for only about 16 years. Therefore, a fluctuation of several per mil in the accuracy or precision of the $\delta^{13}C$ value generated by a radiocarbon laboratory is still within the one sigma standard deviation commonly reported for ^{14}C ages (typically 50–100 years). In contrast, a shift of several per mil in $\delta^{13}C$ from a soil sample indicates about a 21 % shift in the ratio of C_4 to C_3 plants! That is not to say that the $\delta^{13}C$ values produced by ^{14}C laboratories are necessarily incorrect, but rather it is not their primary goal to insure the level of accuracy and precision for paleoenvironmental reconstruction. If the user wishes to obtain $\delta^{13}C$ results for paleoenvironmental analysis, it is important to discuss the matter with the ^{14}C laboratory to obtain assurances as to the desired results.

Bibliography

Amundson, R. G., Chadwick, O. A., Sowers, J. M., and Doner, H. E., 1988. Relationship between climate and vegetation and the stable isotope chemistry of soils in the eastern Mojave Desert, Nevada. *Quaternary Research*, **29**(3), 245–254.

Amundson, R., Stern, L., Baisden, T., and Wang, Y., 1998. The isotopic composition of soil and soil-respired CO_2. *Geoderma*, **82** (1–2), 83–114.

Balesdent, J., and Mariotti, A., 1996. Measurement of soil organic matter turnover using ^{13}C abundance. In Boutton, T. W., and Yamasaki, S. (eds.), *Mass Spectrometry of Soils*. New York: Marcel Dekker, pp. 83–111.

Bernoux, M., Cerri, C. C., Neill, C., and de Moraes, J. F. L., 1998. The use of stable carbon isotopes for estimating soil organic matter turnover rates. *Geoderma*, **82**(1–3), 43–58.

Birkeland, P. W., 1999. *Soils and Geomorphology*, 3rd edn. New York: Oxford University Press.

Boutton, T. W., 1991a. Stable carbon isotope ratios of natural materials. II. Atmospheric, terrestrial, marine, and freshwater environments. In Coleman, D. C., and Fry, B. (eds.), *Carbon Isotope Techniques*. San Diego: Academic, pp. 173–185.

Boutton, T. W., 1991b. Stable carbon isotope ratios of natural materials. I. Sample preparation and mass spectrometric analysis. In Coleman, D. C., and Fry, B. (eds.), *Carbon Isotope Techniques*. San Diego: Academic, pp. 155–171.

Boutton, T. W., 1996. Stable carbon isotope ratios of soil organic matter and their use as indicators of vegetation and climate change. In Boutton, T. W., and Yamasaki, S. (eds.), *Mass Spectrometry of Soils*. New York: Marcel Dekker, pp. 47–82.

Boutton, T. W., Archer, S. R., Midwood, A. J., Zitzer, S. F., and Bol, R., 1998. δ^{13}C values of soil organic carbon and their use in documenting vegetation change in a subtropical savanna ecosystem. *Geoderma*, **82**(1–3), 5–41.

Buol, S. W., Southard, R. J., Graham, R. C., and McDaniel, P. A., 2011. *Soil Genesis and Classification*, 6th edn. Chichester: Wiley.

Cerling, T. E., 1984. The stable isotopic composition of modern soil carbonate and its relationship to climate. *Earth and Planetary Science Letters*, **71**(2), 229–240.

Cerling, T. E., 1992. Development of grasslands and savannas in East Africa during the Neogene. *Palaeogeography Palaeoclimatology Palaeoecology*, **97**(3), 241–247.

Cerling, T. E., and Quade, J., 1993. Stable carbon and oxygen isotopes in soil carbonates. In Swart, P. K., Lohmann, K. C., McKenzie, J., and Savin, S. (eds.), *Climate Change in Continental Isotopic Records*. Washington, DC: American Geophysical Union. Geophysical Monograph, Vol. 78, pp. 217–231.

Cerling, T. E., Quade, J., Wang, Y., and Bowman, J. R., 1989. Carbon isotopes in soils and palaeosols as ecology and palaeoecology indicators. *Nature*, **341**(6238), 138–139.

Cerling, T. E., Solomon, D. K., Quade, J., and Bowman, J. R., 1991. On the isotopic composition of carbon in soil carbon dioxide. *Geochimica Cosmochimica et Acta*, **55**(11), 3403–3405.

Cerling, T. E., Wang, Y., and Quade, J., 1993. Expansion of C4 ecosystems as an indicator of global ecological change in the late Miocene. *Nature*, **361**(6410), 344–345.

Cole, D. R., and Monger, H. C., 1994. Influence of atmospheric CO_2 on the decline of C4 plants during the last deglaciation. *Nature*, **368**(6471), 533–536.

Fredlund, G. G., and Tieszen, L. L., 1997. Phytolith and carbon isotope evidence for late quaternary vegetation and climate change in the southern Black Hills, South Dakota. *Quaternary Research*, **47**(2), 206–217.

Hall, S. A., and Penner, W. L., 2013. Stable carbon isotopes, C3–C4 vegetation, and 12,800 years of climate change in central New Mexico, USA. *Palaeogeography Palaeoclimatology Palaeoecology*, **369**, 272–281.

Hoefs, J., 1987. *Stable Isotope Geochemistry*, 3rd edn. Berlin: Springer. Minerals and Rocks, Vol. 9.

Humphrey, J. D., and Ferring, C. R., 1994. Stable isotopic evidence for latest pleistocene and holocene climatic change in north-central Texas. *Quaternary Research*, **41**(2), 200–213.

Kelly, E. F., Yonker, C., and Marino, B., 1993. Stable carbon isotope composition of paleosols: application to holocene. In Swart, P. K., Lohmann, K. C., McKenzie, J., and Savin, S. (eds.), *Climate Change in Continental Isotopic Records*. Washington, DC: American Geophysical Union. Geophysical Monograph, Vol. 78, pp. 233–239.

Marino, B. D., McElroy, M. B., Salawitch, R. J., and Spaulding, W. G., 1992. Glacial-to-interglacial variations in the carbon isotopic composition of atmospheric CO_2. *Nature*, **357**(6378), 461–466.

Marion, G. M., Introne, D. S., and Van Cleve, K., 1991. The stable isotope geochemistry of $CaCO_3$ on the Tanana River floodplain of interior Alaska, U.S.A.: composition and mechanisms of formation. *Chemical Geology: Isotope Geoscience Section*, **86**(2), 97–110.

Midwood, A. J., and Boutton, T. W., 1998. Soil carbonate decomposition by acid has little effect on δ^{13}C of organic matter. *Soil Biology and Biochemistry*, **30**(10–11), 1301–1307.

Monger, H. C., 1995. Pedology in arid lands archaeological research: an example from southern New Mexico-western Texas. In Collins, M. E., Carter, B. J., Gladfelter, B. G., and Southard, R. J. (eds.), *Pedological Perspectives in Archaeological Research*. Madison: Soil Science Society of America. SSSA Special Publication, Vol. 44, pp. 35–50.

Nadelhoffer, K. J., and Fry, B., 1988. Controls on natural nitrogen-15 and carbon-13 abundances in forest soil organic matter. *Soil Science Society of America Journal*, **52**(6), 1633–1640.

Nordt, L. C., 2001. Stable C and O isotopes in soils: applications for archaeological research. In Goldberg, P., Holliday, V. T., and Ferring, C. R. (eds.), *Earth Sciences and Archaeology*. New York: Kluwer/Plenum Publishers, pp. 419–448.

Nordt, L. C., Boutton, T. W., Hallmark, C. T., and Waters, M. R., 1994. Late quaternary vegetation and climate changes in central Texas based on the isotopic composition of organic carbon. *Quaternary Research*, **41**(1), 109–120.

Nordt, L. C., Wilding, L. P., Hallmark, C. T., and Jacob, J. S., 1996. Stable carbon isotope composition of pedogenic carbonate and their use in studying pedogenesis. In Boutton, T. W., and Yamasaki, S. (eds.), *Mass Spectrometry of Soils*. New York: Marcel Dekker, pp. 133–154.

Nordt, L. C., Hallmark, T. C., Wilding, L. P., and Boutton, T. W., 1998. Quantifying pedogenic carbonate accumulations using stable carbon isotopes. *Geoderma*, **82**(1–3), 115–136.

Nordt, L., von Fischer, J., and Tieszen, L., 2007. Late quaternary temperature record from buried soils of the North American Great Plains. *Geology*, **35**(2), 159–162.

Nordt, L., von Fischer, J., Tieszen, L., and Tubbs, J., 2008. Coherent changes in relative C_4 plant productivity and climate during the late quaternary in the North American Great Plains. *Quaternary Science Reviews*, **27**(15–16), 1600–1611.

Nordt, L. C., Collins, M., Monger, H., and Fanning, D., 2011. Entisols. In Huang, P. M. (ed.), *Handbook of Soil Science*, 2nd edn. Boca Raton: CRC Press, pp. 33–49–33–63.

Quade, J., Cerling, T. E., and Bowman, J. R., 1989. Systematic variations in the carbon and oxygen isotopic composition of pedogenic carbonate along elevation transects in the southern Great

Basin, United States. *Geological Society of America Bulletin*, **101**(4), 464–475.
Teeri, J. A., and Stowe, L. G., 1976. Climatic patterns and the distribution of C_4 grasses in North America. *Oecologia*, **23**(1), 1–12.
Trumbore, S. E., 1996. Applications of accelerator mass spectrometry to soil science. In Boutton, T. W., and Yamasaki, S. (eds.), *Mass Spectrometry of Soils*. New York: Marcel Dekker, pp. 311–339.
Vepraskas, M. J., 1994. *Redoximorphic Features for Identifying Aquic Conditions*. Raleigh: North Carolina Agricultural Research Service, North Carolina State University. Technical Bulletin, Vol. 301.
Von Fischer, J. C., Tieszen, L. L., and Schimel, D. S., 2008. Climate controls on C_3 vs. C_4 productivity in North American grasslands from carbon isotope composition of soil organic matter. *Global Change Biology*, **14**(5), 1141–1155.
Wang, Y., Cerling, T. E., and Effland, W. R., 1993. Stable isotope ratios of soil carbonate and soil organic matter as indicators of forest invasion of prairie near Ames, Iowa. *Oecologia*, **95**(3), 365–369.
West, L. T., Drees, L. R., Wilding, L. P., and Rabenhorst, M. C., 1988. Differentiation of pedogenic and lithogenic carbonate forms in Texas. *Geoderma*, **43**(2–3), 271–287.

Cross-references

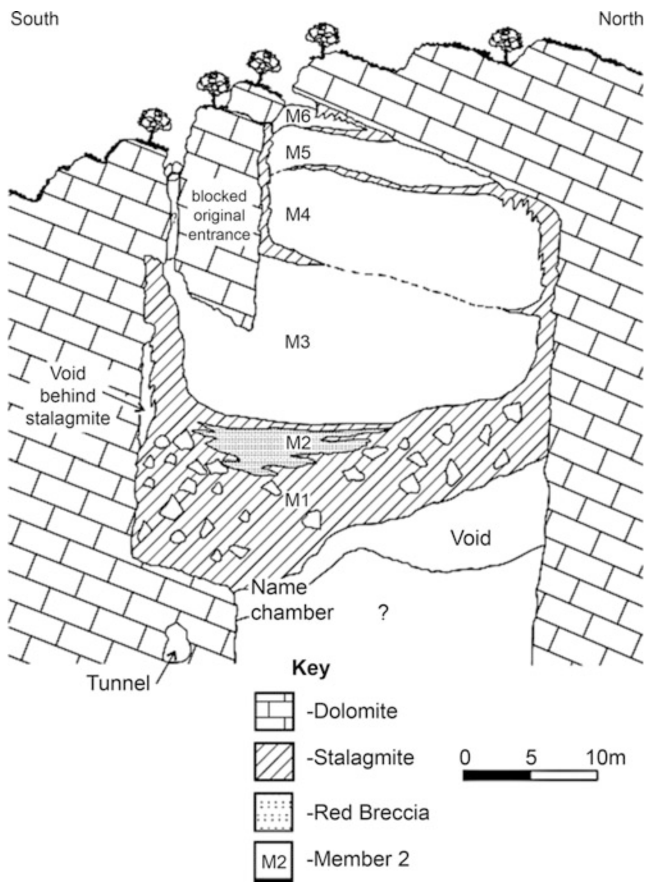
Soils

STERKFONTEIN/SWARTKRANS/KROMDRAAI

Dominic Stratford
School of Geography, Archaeology and Environmental Studies, University of the Witwatersrand, Witwatersrand, Johannesburg, South Africa
Sterkfontein Caves Palaeoanthropological Site, Johannesburg, South Africa

Definition

The paleoanthropological sites of Sterkfontein, Swartkrans, and Kromdraai lie within two miles of each other along the Blaauwbank River valley about 50 km northwest of Johannesburg, South Africa, in the UNESCO World Heritage Site known as the Cradle of Humankind. From a paleoanthropological perspective, all three sites have been researched for over 50 years and have yielded specimens of *Australopithecus africanus* and *Australopithecus prometheus* (at Sterkfontein) (Clarke, 2013), *Paranthropus robustus* (at Sterkfontein, Swartkrans, and Kromdraai) (Kuman and Clarke, 2000; Braga and Thackeray, 2003; Pickering et al., 2012), and early *Homo* (at Sterkfontein, Swartkrans, and Kromdraai) (Kuman and Clarke, 2000; Braga and Thackeray, 2003; Grine, 2005). In addition to large assemblages of associated fauna, these sites are of particular interest because they have yielded three of the earliest stone tool assemblages known from South Africa and represent rare examples of sites with associated hominins, fauna, and archaeological material.



Sterkfontein/Swartkrans/Kromdraai, Figure 1 The Sterkfontein Formation (From Clarke, 2006). Originally described by Partridge (1978), this chrono-stratigraphic sequence of the Sterkfontein deposits has been repeatedly updated. The Sterkfontein Formation comprises six main deposits: Member 1 through Member 6 (M1 through M6). M1 is an authigenic deposit formed from the vadose collapse of the cave. Member 2 is currently the earliest allogenic and fossiliferous deposit and has yielded the StW 573 *Australopithecus* skeleton. M3 has not yet been strategically sampled but is highly fossiliferous. M4 is the main *Australopithecus*-bearing deposit and the richest single locality for the hominin genera in the world. M5 contains both an Oldowan and Early Acheulean stone tool assemblage.

These sites, especially Sterkfontein, have been notoriously difficult to date with absolute techniques. Traditionally, a biostratigraphic approach calibrated using East African biochronological sequences has been the dominant indicator of the relative age of the fossils within the deposits. Absolute techniques have focused on either U-Th, U-Pb, or paleomagnetic dating of interbedded or ‘capping’ flowstones and have assumed that these formations represent boundary units between deposits (e.g., Pickering and Kramers, 2010; Herries and Shaw, 2011). This undoubtedly can be applied where true ‘capping’

Sterkfontein/Swartkrans/Kromdraai, Figure 2 A typical vertical opening (avens type) to the Sterkfontein caves, the floor of which lies 25 m below. Notice the concentrated vegetation around the opening – a feature that would have provided shelter for primates, carnivores, and hominins in the past. The opening measures approximately 2 × 3 m (Photo by D. Stratford).

flowstones are found (e.g., Malapa); however, at Sterkfontein many important flowstones have been found to be intrusive and therefore misleading since they would then postdate the sediments into which they grew (e.g., Bruxelles et al., 2014). Recent cosmogenic dating of allogenic components directly associated with deposit sediment (Granger et al., 2015) has led to encouraging results for the oldest hominin fossils and the Oldowan stone tool assemblage, placing the StW 573 australopithecine skeleton at 3.67 ± 0.16 million years ago, far earlier than the intrusive flowstone which has been dated at about 2.2 million years ago. The earliest stone tools at Sterkfontein reveal a date of 2.18 ± 0.21 million years ago based on the same method.

All paleoanthropological assemblages from these sites, and all sites within the Cradle of Humankind area, were yielded from allogenic sediments (externally derived, as opposed to authigenic) accumulated within deep karst caves in the Monte Cristo Formation comprising the 2.6 Ga Malmani dolomitic limestone (Figure 1). The caves, which have characteristic morphologies, formed under phreatic conditions (below the water table) as deep chambers and tall, narrow passages oriented along fissures within the heavily faulted host rock. Passages generally run east to west at these sites. Vadose collapse (above the water table) focused on the same faults enlarged the chambers while they were still below ground and eventually created avens-type openings (small, high, and vertical) in the ceilings of the caves. Once further collapse opened them to the landscape (Figure 2), the caves accumulated sediments, bones, and stone tools that formed large talus deposits on the cave floor over the course of several million years. The nature of the openings meant that they were still mostly inaccessible to fauna and hominins, so bones were accumulated through numerous taphonomic processes, while artifacts were gradually washed into the caves from the area immediately around the cave entrances. Gradual erosion of the landscape, combined with early twentieth-century mining of the travertine deposits, removed the cave roofs and exposed the interred fossil- and artifact-bearing deposits. The paleoanthropological importance of these deposits was first recognized at Sterkfontein in 1936 by Dr. Robert Broom (Broom, 1936).

The changing location, size, and number of openings into the caves have important implications for both (1) the accumulation of sediments, fauna, hominins, and artifacts, which have been deposited through a diverse range of processes, and (2) the resultant stratigraphy of the deposits, which is notoriously complex. The development of cave taphonomy (Brain, 1981) has helped clarify the faunal accumulation processes and in all three sites deathtrap, and carnivore activity (particularly leopard) around the cave entrances has played an integral role in the accumulation of bones from hominins, other primates, and bovids. The relatively restricted catchment area of the cave openings means that artifact presence in the deposits is representative of nearby hominin activity. The presence of artifacts at these sites and their general absence in the other Cradle of Humankind sites may be a result of proximity to river gravels which lie about 300 m from all three sites and provided the preferred raw materials during the Earlier Stone Age (ESA) (Kuman, 2003). Despite this proximity, raw material reduction strategies and levels vary between the sites as evidenced by the core form representation. Generally, bipolar and casual cores dominate the quartz assemblages with relatively high levels of reduction. In contrast, polyhedral and casual cores prevail in quartzite and are often left with remaining unstruck platforms. This pattern can be generally described as resulting from a highly localized and easily sourced raw material.

Sterkfontein and Swartkrans have yielded comparably sized Oldowan assemblages but document slightly different raw material procurement and utilization strategies. Both assemblages reveal a preference for quartz as a raw material, with a higher usage of chert in the Swartkrans collection. This relative preference may be due to the higher abundance of chert in the dolomite exposed within the landscape close to Swartkrans. Assemblage size profiles in the Oldowan assemblages of both Sterkfontein and Swartkrans demonstrate high levels of site capture, that is, mostly intact assemblages were deposited within the caves, and all components (including small flaking debris) are recoverable to some degree from the sediments thereby indicating a relatively high assemblage integrity. Variation in the condition of recovered artifacts may suggest that components of the assemblages were exposed on the landscape surface for differing intervals of time before being washed into the cave. Both collections suffered postdepositional winnowing of smaller flaking debris once in the cave. In the case of the Sterkfontein Oldowan, some of this debris was winnowed and redeposited into another chamber 20 m below. The Oldowan assemblages are associated with *Paranthropus robustus* at Sterkfontein and Swartkrans and with *Homo* at Swartkrans.

The Early Acheulean of Sterkfontein indicates a change in raw material procurement and knapping location, as hominins utilized quartzite cobbles sourced from the river gravels and may have conducted primary flaking phases closer to the gravels as suggested by the absence of small flaking debris. Within this deposit, we find one of the only positive associations between the Early Acheulean and *Homo ergaster* (StW 80) in Southern Africa.

The Kromdraai assemblages are significantly smaller with only two artifacts yielded from the Kromdraai B site, which, based on biostratigraphy, is roughly contemporaneous with the Oldowan at Sterkfontein and Swartkrans. Local conditions may have been very wet, limiting the attractiveness of the site to hominins. Kromdraai A is roughly equivalent in time to the Acheulean of Sterkfontein and has yielded 100 artifacts (Kuman et al., 1997). Quartz dominates this small sample, and those artifacts with remaining cortex indicate procurement from the river gravels. The size profile of the assemblage shows a dominance of flakes and core forms with a noticeable absence of small flaking debris, which suggests either pre-depositional removal of small flaking debris indicative of poor site catchment or postdepositional erosion to lower, unexcavated areas of the deposit or cave.

Bibliography

Braga, J., and Thackeray, J. F., 2003. Early *Homo* at Kromdraai B: probabilistic and morphological analysis of the lower dentition. *Comptes Rendus Palevol*, **2**(4), 269–279.

Brain, C. K., 1981. *The Hunters or the Hunted? An Introduction to African Cave Taphonomy*. Chicago: University of the Chicago Press.

Broom, R., 1936. New fossil anthropoid skull from South Africa. *Nature*, **138**(3490), 486–488.

Bruxelles, L., Clarke, R. J., Maire, R., Ortega, R., and Stratford, D. J., 2014. Stratigraphic analysis of the Sterkfontein StW 573 *Australopithecus* skeleton and implications for its age. *Journal of Human Evolution*, **70**, 36–48.

Clarke, R. J., 2006. A deeper understanding of the stratigraphy of Sterkfontein fossil hominid site. *Transactions of the Royal Society of South Africa*, **61**(2), 111–120.

Clarke, R. J., 2013. *Australopithecus* from Sterkfontein Caves, South Africa. In Reed, K. E., Fleagle, J. G., and Leakey, R. E. (eds.), *The Paleobiology of Australopithecus*. Dordrecht: Springer, pp. 105–123.

Granger, D. E., Gibbon, R. J., Kuman, K., Clarke, R. J., Bruxelles, L., and Caffee, M. W., 2015. New cosmogenic burial ages for Sterkfontein Member 2 *Australopithecus* and Member 5 Oldowan. *Nature*, **522**(7554), 85–88. doi:10.1038/nature14268.

Grine, F. E., 2005. Early Homo at Swartkrans, South Africa: a review of the evidence and an evaluation of recently proposed morphs. *South African Journal of Science*, **101**(1–2), 43–52.

Herries, A. I. R., and Shaw, J., 2011. Palaeomagnetic analysis of the Sterkfontein palaeocave deposits: implications for the age of the hominin fossils and stone tool industries. *Journal of Human Evolution*, **60**(5), 523–539.

Kuman, K., 2003. Site formation in the early South African Stone Age sites and its influence on the archaeological record. *South African Journal of Science*, **99**(5–6), 251–254.

Kuman, K., and Clarke, R. J., 2000. Stratigraphy, artefact industries and hominid associations for Sterkfontein Member 5. *Journal of Human Evolution*, **38**(6), 827–847.

Kuman, K., Field, A. S., and Thackeray, J. F., 1997. Discovery of new artefacts at Kromdraai. *South African Journal of Science*, **93**(4), 187–193.

Partridge, T. C., 1978. Re-appraisal of lithostratigraphy of Sterkfontein hominid site. *Nature*, **275**(5678), 282–287.

Pickering, R., and Kramers, J. D., 2010. Re-appraisal of the stratigraphy and determination of new U-Pb dates for the Sterkfontein hominin site, South Africa. *Journal of Human Evolution*, **59**(1), 70–86.

Pickering, T. R., Heaton, J. L., Clarke, R. J., Sutton, M. B., Brain, C. K., and Kuman, K., 2012. New hominid fossils from Member 1 of the Swartkrans formation, South Africa. *Journal of Human Evolution*, **62**(5), 618–628.

Cross-references

Cave Settings
Cosmogenic Isotopic Dating
Isochron Dating
Speleothems
U-Series Dating

STONEHENGE

Mike Parker Pearson
Institute of Archaeology, University College London, London, UK

Definition

Stonehenge is the world's most famous stone circle, dating from the later prehistoric period (the Neolithic,

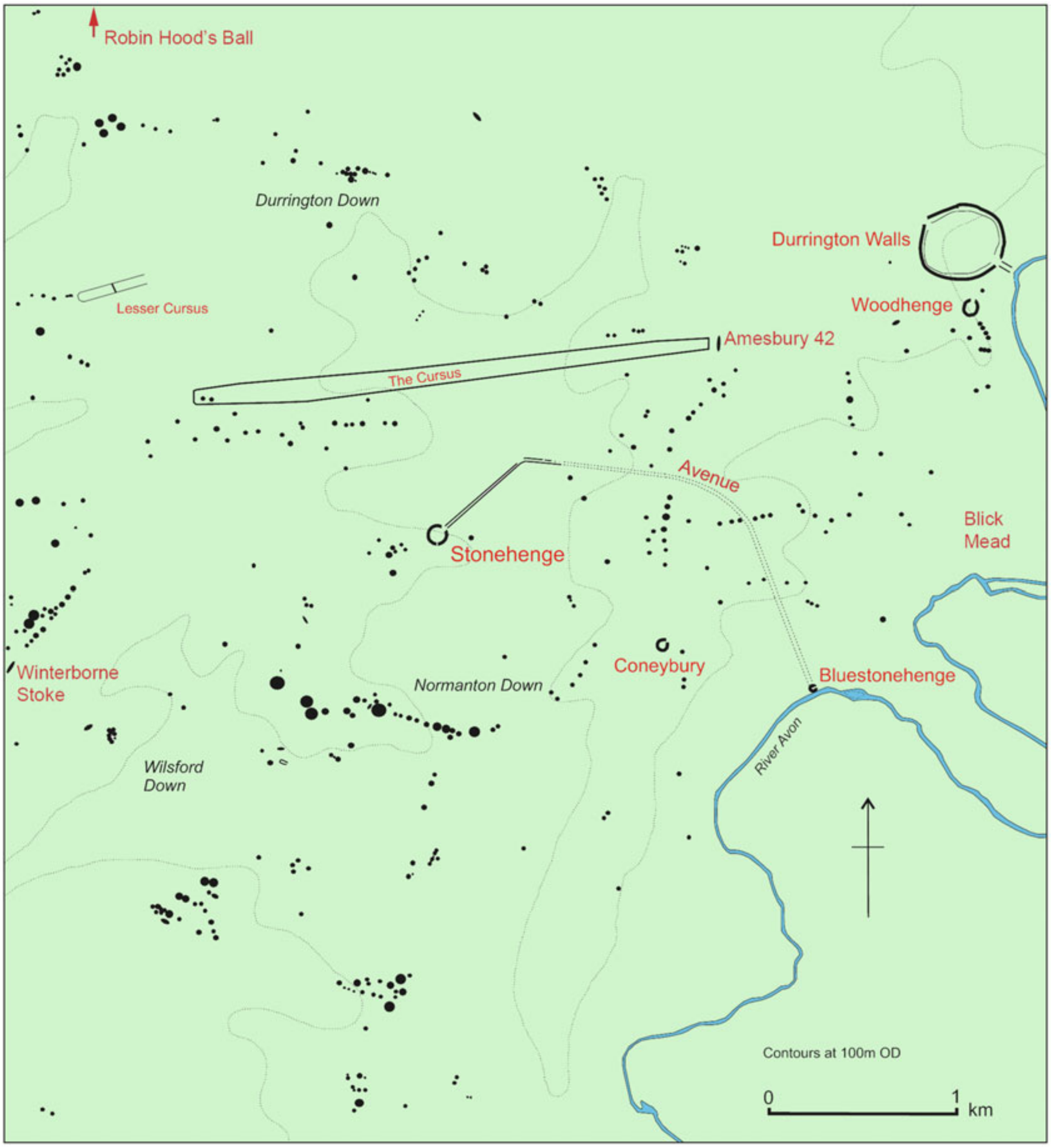
Stonehenge, Figure 1 Stonehenge viewed from the northeast, looking towards the direction of midwinter solstice sunrise (Photo by Adam Stanford of Aerial-Cam Ltd.)

Chalcolithic, and Early Bronze Age). It was built in five chronologically distinct stages, dated by statistical modeling of radiocarbon dates on antler picks deposited in construction contexts associated with each of the stages (Darvill et al., 2012).

Stonehenge is located on the chalk uplands of Salisbury Plain in southern Britain on high ground about a mile northwest of the River Avon. These chalk uplands never developed the dense canopy of postglacial forest found elsewhere in Britain, and Stonehenge's first stage was built within a largely treeless landscape during the interval 3000–2755 cal BC. At this time, Stonehenge consisted of a circular bank and ditch enclosing a ring of 56 pits known as Aubrey Holes, named after the seventeenth century antiquary John Aubrey who surveyed the site. More than 300 postholes found within the center of the monument, within the enclosure's northeast entrance, and forming a passageway towards its southern entrance are also thought to date to this earliest stage (although the only one with any finds contained animal bones radiocarbon dated to the monument's second stage). Holes to support standing stones of sarsen (sandstone of Tertiary silcrete from the local area) outside the northeast entrance and within the center of the monument probably date to this first stage as well. Similarly, there is evidence that "bluestones" – derived from the Preseli Hills in western Wales consisting of mostly spotted dolerite (diorite) as well as unspotted dolerite, rhyolite, volcanic ash, and sandstone – were positioned in the Aubrey Holes in Stage 1 (3000–2920 cal BC).

The second stage of Stonehenge (2620–2480 cal BC) consists of a central group of five sarsen trilithons arranged in a horseshoe plan, surrounded by a setting of bluestones (the Q and R Holes, known as the double bluestone circle, although it appears to have consisted of a single circle along its southwestern circumference). These were surrounded by a circle of standing sarsens connected to each other by stone lintels. Mortices and tenons were carved into these dressed stones of the trilithons and circle, perhaps to give them the appearance of carpentry in stone. There were a further three stages of construction (Stage 3: inner bluestone circle and Stonehenge avenue 2480–2280 cal BC; Stage 4: inner bluestone oval and outer bluestone circle 2280–2020 cal BC; and Stage 5: Y and Z Holes 2020–1520 cal BC), but Stonehenge's essential appearance today derives from Stage 2 (Figure 1).

Excavations in 2008 revealed that Stonehenge was positioned at the southwestern end of a pair of two chalk ridges about 200 m long, natural landforms coincidentally running northeast-southwest along the axis of the midwinter sunset/midsummer sunrise (the monument's architectural axis from Stage 2 onwards). The two ridges were later embellished by the banks and ditches of an avenue in Stage 3, leading along the solstice axis for 500 m before turning towards the River Avon. At the riverside, the



Stonehenge, Figure 2 Stonehenge in its landscape, showing its geographical relationship with the Avenue and Bluestonehenge, Durrington Walls, Woodhenge, and other prehistoric monuments.

avenue arrived at a smaller stone circle, Bluestonehenge, whose 25 or so stones were removed in Stage 3; the shapes and sizes of the holes left by the removed pillars attest to the circle's original existence. The dismantled circle of Bluestonehenge was then enclosed by the bank and ditch of a small henge with an east-facing entrance (Figure 2).

Stonehenge is the largest known burial ground of the third millennium BC in Britain. Some 63 cremation deposits and an inhumation have been recovered from within the enclosing ditch and the interior, dating to Stages 1–3. Many of the cremation deposits were placed in the Aubrey Holes, either within the chalk packing around bluestone pillars or against the sides of already inserted pillars. Most of the burials were those of adult men and women, with remains of only five subadults. Of the few grave goods, one is a beautiful macehead of banded gneiss, likely to have come from the far north or west of Britain.

Remains of a large settlement, consisting of houses and timber circles, have been found nearby at Durrington Walls and Woodhenge, upstream along the Avon; they are broadly contemporary with Stonehenge Stage 2 and are thought to have been inhabited by its builders (Parker Pearson, 2012). Feasting debris from this 17-ha settlement includes bones of cattle and pigs; strontium isotope analysis of their tooth enamel demonstrates that they were brought from different regions of Britain, some of them hundreds of miles away (Viner et al., 2010). Analysis of tooth wear in the pigs reveals that most were culled during winter (Wright et al., 2014).

The first written reference to Stonehenge was in about 1130 by Henry of Huntingdon. The earliest recorded excavations at Stonehenge are those of the Duke of Buckingham in the early seventeenth century, but modern excavations were not carried out until the twentieth century, first by William Gowland in 1901 and then by William Hawley in 1919–1926. Richard Atkinson, accompanied by Stuart Piggott and J. F. S. Stone, excavated Stonehenge during the 1950–1970s, with the results being written up and published after Atkinson's death (Cleal et al., 1995). Aside from various salvage excavations within the Stonehenge World Heritage Site from the 1960s onwards, the next major research investigation was the Stonehenge Riverside Project (2003–2009). This was followed by the Feeding Stonehenge Project (2010–2013) and the Stones of Stonehenge Project (2011–2016), both investigating the sourcing of people, animals, and materials involved in building the monument. Since 2008, a number of other projects have carried out laser scanning of the stones, geophysical and topographic survey of Stonehenge's environs, excavation of a nearby Mesolithic site, and keyhole excavation inside Stonehenge itself.

The bluestones were brought 180 miles from Pembrokeshire in west Wales, the longest distance moved by megaliths in prehistory. Two of the outcrops from which some of them were quarried have been identified through geochemical and petrological provenance and archaeological excavation (Ixer and Bevins, 2011; Bevins et al., 2014; Parker Pearson et al., 2015). The dominant source of spotted dolerite pillars is Carn Goedog on the north flank of the Preseli Mountains. A source for one of the types of rhyolite at Stonehenge has been identified on an outcrop at Craig Rhosyfelin, beside a stream flowing northwards from Preseli. Excavations in 2011–2015 revealed quarrying activity associated with an occupation area dated by radiocarbon assay on hazelnuts to 3500–3120 cal BC, several centuries before the bluestones were erected at Stonehenge. This raises the possibility that the bluestones were initially installed within a monument complex, as yet undetected, somewhere north of the Preseli Mountains.

Just how the bluestones were taken to Stonehenge has long been a matter of speculation. The hypothesis that these 2-t monoliths were taken south from the Preseli Mountains to Milford Haven and then floated around the coast is contradicted by the evidence for quarries on the north side of Preseli and by the reassignment of the sandstone Altar Stone's origins from the Cosheston Beds of Milford Haven to the Devonian Senni Beds, most likely in the area of the Brecon Beacons (Ixer and Turner, 2006). An alternative to sea transport is movement overland along the Welsh valleys, fording the River Severn at Gloucester, and thence to Salisbury Plain. Ethnographic cases from South and Southeast Asia reveal that monoliths of this size can be easily "stretchered" on latticed wooden frameworks by large teams of carriers, thereby protecting such thin pillars from shock caused by direct or indirect contact with the ground.

For over 300 years, the main source of Stonehenge's sarsens has been thought to be the Marlborough Downs, 20 miles north of Stonehenge in the vicinity of Avebury henge and stone circle. In the 1720s, William Stukeley claimed to have seen the holes from which Stonehenge's sarsens were extracted, and he also recorded a group of roughly dressed sarsens on the north bank of the River Kennet that he thought were originally destined for Stonehenge. Despite this promising early start, there has been very little geochemical or petrological work on Stonehenge's sarsens. It is possible that some of them might come from silcrete beds scattered across southern England from Kent to Dorset, though the sources of the largest blocks of tabular sarsen have long been known to have lain on the higher ground of the Marlborough Downs.

The purpose of Stonehenge has been mulled over since Henry of Huntingdon's day. His contemporary, Geoffrey of Monmouth, wrote in his pseudohistory of the kings of Britain that it was built as a memorial to the British dead treacherously slain by Saxons and that the wizard Merlin and 15,000 men went to Ireland to take the stones from a circle, *Chorea Gigantum* (the giants' dance) on Mount Killaurus, built by giants who cured their illnesses by bathing in water splashed on the stones.

In the seventeenth and eighteenth centuries, John Aubrey and later William Stukeley proposed that Stonehenge was a temple. Realizing that it was prehistoric but unaware of its true antiquity, they drew on Caesar's account of his invasion of Britain in 55 BC to describe its priests as druids. In 1965, the astronomer Gerald Hawkins crystallized the growing awareness of Stonehenge's astronomical aspects to propose that it was an observatory for computing solar and lunar eclipses amongst other heavenly events. Although Hawkins' theory was not accepted by most scholars, the understanding that Stonehenge might be a temple to the sun was prominent for a while amongst archaeologists.

Geoffrey of Monmouth's reference to the stones' healing properties led archaeologists Tim Darvill and Geoff Wainwright to propose that Stonehenge was a place of the living, with the "healing" bluestones brought to Stonehenge to create a place of pilgrimage for the sick. The discovery that the bluestones' first installation at Stonehenge was most likely in the Aubrey Holes, intimately associated with the remains of the dead renders this theory unlikely.

Stonehenge is one of many Neolithic monuments in Britain and Western Europe that were built of stone and contain the remains of the dead. In contrast, houses and settlements at this time, such as Durrington Walls, were built of timber. This raises the possibility that stone monuments were considered to be metaphors of the permanent and eternal world of the ancestors. Certain astronomical orientations may also have become associated with this unchanging world of the afterlife. The large stone tombs of Newgrange in Ireland and Maes Howe in Orkney were built around this time, with their passages aligned on the midwinter solstice sunrise and sunset. Stonehenge's first stage was perhaps built as a monument to unite ancestries across southern Britain from west Wales and Salisbury Plain, by incorporating stones that represented these different identities.

Stonehenge was built during a period of growing commonality in material culture styles across Britain at a time when declining links across the English Channel appear to have left Britain in isolation. The far-flung origins of some of the Durrington Walls cattle and pigs in Stage 2 are indicative of its role in uniting groups from across the entire country. Although Stonehenge continued as a place of burial after 2500 BC, these burials were limited to its periphery. No longer a monument to the recently dead, its role in Stage 2 appears to have changed to that of a symbolic meeting place of the more ancient ancestors (Parker Pearson, 2012). If Stage 2 was a monument to island-wide unification of Britain's diverse ancestries, then its impact was short-lived since the construction of this second stage was closely followed by the arrival of Bell Beaker migrants from the Continent, bringing metallurgy and effecting widespread cultural change.

Bibliography

Bevins, R. E., Ixer, R. A., and Pearce, N. J. G., 2014. Carn Goedog is the likely major source of Stonehenge doleritic bluestones: evidence based on compatible element geochemistry and principal components analysis. *Journal of Archaeological Science*, **42**, 179–193.

Cleal, R. M. J., Walker, K. E., and Montague, R., 1995. *Stonehenge in Its Landscape: Twentieth-Century Excavations*. London: English Heritage.

Darvill, T. C., Marshall, P., Parker Pearson, M., and Wainwright, G. J., 2012. Stonehenge remodelled. *Antiquity*, **86**(334), 1021–1040.

Ixer, R. A., and Bevins, R. E., 2011. Craig Rhos-y-felin, Pont Saeson is the dominant source of the Stonehenge rhyolitic 'debitage'. *Archaeology in Wales*, **50**, 21–31.

Ixer, R. A., and Turner, P., 2006. A detailed re-examination of the petrography of the Altar Stone and other non-sarsen sandstones from Stonehenge as a guide to their provenance. *Wiltshire Archaeological and Natural History Magazine*, **99**, 1–9.

Parker Pearson, M., 2012. *Stonehenge: Exploring the Greatest Stone Age Mystery*. London: Simon & Schuster.

Parker Pearson, M., Bevins, R., Ixer, R., Pollard, J., Richards, C., Welham, K., Chan, B., Edinborough, K., Hamilton, D., Macphail, R., Schlee, D., Simmons, E., and Smith, M., 2015. Craig Rhos-y-felin: a Welsh bluestone megalith quarry for Stonehenge. *Antiquity*, **89**(348), 1331–1352.

Viner, S., Evans, J., Albarella, U., and Parker Pearson, M., 2010. Cattle mobility in prehistoric Britain: strontium isotope analysis of cattle teeth from Durrington Walls (Wiltshire, Britain). *Journal of Archaeological Science*, **37**(11), 2812–2820.

Wright, E., Viner-Daniels, S., Parker Pearson, M., and Albarella, U., 2014. Age and season of pig slaughter at Late Neolithic Durrington Walls (Wiltshire, UK) as detected through a new system for recording tooth wear. *Journal of Archaeological Science*, **52**, 497–514.

STRATIGRAPHY

Paul Goldberg[1], Vance T. Holliday[2] and Rolfe D. Mandel[3]
[1]Department of Archaeology, Emeritus at Boston University, Boston, MA, USA
[2]Anthropology and Departments Geosciences, University of Arizona, Tucson, AZ, USA
[3]Department of Anthropology, University of Kansas, Lawrence, KS, USA

Introduction

Stratigraphy has an intuitive meaning to archaeologists even if specific definitions vary (see "Archaeological Stratigraphy" entry in this volume). In the more classical geological literature, stratigraphy tends to be viewed at the regional scale: "The crux of much of stratigraphy is the spatial relationships of rocks over geographic areas" (Schoch, 1989). It also encompasses physical characteristics of sediments that include notions of space and time:

> [S]tratigraphy in the broadest sense is the science dealing with strata and could be construed to cover all aspects—including textures, structures, and composition.... Stratigraphers are mainly concerned with the stratigraphic order and the construction of the geologic column. Hence the central problems of stratigraphy are temporal and involve the local succession of beds (order of superposition), the correlation of local sections, and the formulation of a column of worldwide validity. Although these are the objectives of stratigraphy, the measurement of thickness and description of gross lithology are commonly considered a part of the stratigrapher's task. (Pettijohn, 1975, 1)

Archaeologists view stratigraphy, deposits, features, and artifacts at the scale of the site and perhaps its immediate surroundings (Stein and Linse, 1993). For them, stratigraphy can be simply, "the natural and cultural layering of the soil at a site" (Hester et al., 1997) (intuitively correct despite the incorrect use of "soil"). Thomas (1998, p. 205) provides a more holistic definition of stratigraphy: "An analytical interpretation of the structure produced by the deposition of geological and/or cultural sediments into layers, or strata." He includes the interpretative aspects, since stratigraphy does not exist by itself. It is something that is recognized somewhat subjectively. Different researchers, depending on their experience and background (archaeologist, geologist, geographer, pedologist, and other environmentalists), might construct different stratigraphic sequences for the same physical stratigraphic

Stratigraphy, Table 1 Types of Stratigraphic Units and their basis of classification

Classificatory basis	Stratigraphic classification Geoarchaeology	Formal subdivisions	Stratigraphic classification Geology	Formal subdivisions
Lithology (physical and/or chemical composition)	Lithologic unit *time-transgressive*	Layer, sub-layer, inclusion; elemental sediment unit	Lithostratigraphic unit *time-transgressive*	Formation, member, bed
Time	Chronostratigraphic unit *specific time interval*	Set, phase, sub-phase	Geochronologic unit *specific time interval*	Eon, era, period, epoch, age
Fossils	Biostratigraphic unit *time-transgressive*	Biozone	Biostratigraphic unit *time-transgressive*	Biozone
Artifacts	Ethnostratigraphic unit *time-transgressive*	Zone, supra-zone, sub-zone	None	None

profile. In the geoarchaeological sector, Waters (1992, p. 60) takes a traditional, geological, and "depositional" viewpoint, emphasizing deposits and soils that are observed principally on a geomorphologic scale: "Stratigraphy is the study of the spatial and temporal relationships between sediments and soils. Stratigraphic sequences are created because depositional environments are dynamic and constantly changing." On this regional scale, stratigraphic study is useful to organize sediments and soils into objectively identifiable packages that can be arranged in some kind of chronological order and absolute age on the basis of temporal markers, such as soil formation, or perhaps erosion. "Parcels" of soils/sediments can be physically (spatially) or temporally linked and integrated over an area, either on the scale of meters or kilometers.

During the latter part of the nineteenth century, classical geologists realized that it was necessary to separate the physical characteristics of a sedimentary rock (i.e., color, texture, and composition) from the time in which it formed. This came about because they came to see based on fossil content that a geological unit can accumulate over a long period of time and be older in one place than in another (diachronous or "time-transgressive" units: Krumbein and Sloss, 1963; Vita-Finzi, 1973). Deltaic deposits, for example, become progressively younger in the seaward direction, even though the overall "deltaic lithologies" do not change radically and horizontally within the area of the delta. To overcome these issues of time and space, stratigraphy recognized a number of different types of stratigraphic units, embodied in the *International Stratigraphic Guide* (Hedberg, 1976; Schoch, 1989) and the *North American Stratigraphic Code* (NACSN, 2005). Table 1 summarizes the most common types of stratigraphic units. Note that the two major groups of units are delineated on the basis of content or physical limits (Group I), as opposed to those units in Group II, which are defined solely on the basis of time. Thus, the units in Group I are derived, for example, from their mineral composition or texture, biological/fossil constituents, soil characteristics, or stratigraphic boundaries or gaps marked by lapses in time (unconformities).

Lithostratigraphy

Lithostratigraphic units are the most basic and ubiquitous. They are relevant to the majority of geoarchaeological situations and are denoted on the basis of lithological characteristics, such as color, texture, composition, thickness, and upper and lower boundaries. They do not imply any notions of time, just the descriptive aspects of the sedimentary bodies. In regional-scale geological contexts, the primary lithostratigraphic unit is the formation, which is one that can be mapped over a region. It can be represented by a 20-m-thick accumulation of alternating beds of clay and silt or by a 2-m-thick massive layer of limestone. Two or more formations that form a consistently uniform lithological package can be combined into a group. On the other hand, formations can be subdivided into smaller units, such as a member, and even finer units, such as a bed. The latter is the smallest lithostratigraphic unit and is lithologically distinct from units above and below it (but see the "Archaeological Stratigraphy" entry in this volume).

On an archaeological scale, which can be on the order of tens (e.g., living structures) to thousands of square meters (e.g., tell or other types of mound) in area, a lithostratigraphic unit can take the form of a centimeter-thick band of red clay underlying a plastered floor from a Bronze Age house. In caves, a layer of rockfall mixed with clay would also be a common type of lithostratigraphic unit.

Biostratigraphy

Biostratigraphic units are delineated on the basis of the fossils they contain, including the appearance, disappearance, or relative abundance of the remnants of former organisms. The fossils can be either plants or animals and marine or terrestrial. For example, the Tertiary period was subdivided by Lyell on the basis of the abundance of fossil molluscan species that are living today. Only 3.5% of Eocene fossils represent currently living forms, whereas during the Pleistocene, about 90% of the species remain extant today (Farrand, 1990).

The fundamental unit in biostratigraphy is the biozone. In archaeological contexts, however, the most common types of biostratigraphic units are those based on plant remains, particularly pollen, and land mammals. Pollen-based biostratigraphic units are referred to as "Pollen Zones" (Bowen, 1978). The most common and widely used biostratigraphic units based on mammal assemblages are "Land Mammal Ages" (Webb et al., 2004). For example, in North America, the Land Mammal Age that encompasses the earliest (Late Pleistocene) human occupation of the continent is the Rancholabrean Land Mammal Age. It is characterized by the appearance of bison (Mead, 2013).

Soil stratigraphy

Soil stratigraphic units (also referred to as pedostratigraphic units) represent a whole buried soil or part of one that exhibits one or more soil horizons (see the "Soil Stratigraphy" entry in this volume) that are preserved in a rock or sediment and are traceable over an extended area (Schoch, 1989; NACSN, 2005). These types of unit, the foremost of which is the geosol, represent relatively short periods of geological time. Hence, they serve as temporal pegs or "marker horizons" that temporally order the relative ages of deposits and events that overlie and underlie the soil (Holliday, 2004). Geosols also have paleoenvironmental significance (Fedoroff and Goldberg, 1982). The interglacial Sangamon soil in the Midwest of the United States has been extensively used as a stratigraphic tool (Birkeland, 1999), and similar such soils have been documented in the United Kingdom by Kemp (1986, 1999). The Barham soil in eastern England, for example, is a clear stratigraphic marker horizon that denotes a major landscape change and climatic degradation (Rose et al., 1985).

Allostratigraphy

Allostratigraphic units are rock or sediment bodies that are overlain and underlain by temporal discontinuities (unconformities). A prevalent case in point is that of stream terrace deposits produced by successive episodes of alluvial deposition followed by erosion that interrupts the continuous accumulation. Allostratigraphic units are a convenient means to map widespread fluvial deposits for example which may be lithologically homogeneous and otherwise difficult to subdivide lithostratigraphically. They constitute a basic component in documenting the Holocene fluvial geoarchaeological history of much of the mid-continental United States (Brown, 1997; Goldberg, 1986; Mandel, 1995; Ferring, 2001). Such fluvial deposits commonly contain archaeological sites and can be traced over several kilometers within the same allostratigraphic unit.

Chronostratigraphy

Chronostratigraphy is organized on the basis of geochronologic units, which are defined solely on the basis of the time interval that they encompass (see the "Chronostratigraphy" entry in this volume). As such, they do not represent actual or specific rocks but more conceptually represent divisions of time. These units are differentiated on the basis of radiometric dating, such as potassium/argon ($^{40}K/^{40}Ar$) – or now argon-argon ($^{40}Ar/^{39}Ar$) – and uranium-series techniques. They can also be temporally sequenced when they contain mixtures of different types of fossils and lithologies. The Quaternary, which includes much of the geoarchaeological record and all of the recent "Ice Ages," represents the last 2.6 Ma (Pillans, 2013). It is subdivided into the well-known subdivisions of the Pleistocene (2.6 my to 11,700 years ago, and including all glacial-interglacial stages except the most recent interglacial) and the Holocene (the past 11,700 years, representing post-glacial time or the current interglacial period).

Climatostratigraphy

Climatostratigraphy (or climostratigraphy) is the classification of deposits based on inferred intervals of climate change (see the "Climatostratigraphy" entry in this volume). In geology, climatostratigraphy is unique to Quaternary geology and geoarchaeology owing to the evidence for dramatic climate changes, particularly glacial-interglacial cycles, during much of human evolution and the rise of modern societies worldwide. Links between climate change and the Quaternary geologic record were in evidence since the early history of geology in the nineteenth century, but research was hampered until the middle of the twentieth century by incomplete stratigraphic sequences and an absence of firm age control for both climate events and geologic records. Climatostratigraphy was revitalized by (1) the advent of deep ocean coring and the establishment of marine oxygen isotope stages of glacial-interglacial cycles, (2) the development of coring into ice sheets and the recognition of finer-scale glacial and interglacial events (e.g., Dansgaard-Oeschger cycles and Heinrich events) (Labeyrie et al., 2013), and (3) the development of an array of numerical dating methods. Cores from the deep ocean and ice sheets now provide standardized reference markers of climate changes against which terrestrial lithostratigraphic and biostratigraphic records can be compared.

Bibliography

Birkeland, P. W., 1999. *Soils and Geomorphology*, 3rd edn. New York: Oxford University Press.

Bowen, D. Q., 1978. *Quaternary Geology: A Stratigraphic Framework for Multidisciplinary Work*. Oxford: Pergamon.

Brown, A. G., 1997. *Alluvial Geoarchaeology: Floodplain Archaeology and Environmental Change. Cambridge Manuals in Archaeology*. Cambridge: Cambridge University Press.

Farrand, W. R., 1990. Origins of Quaternary-Pleistocene-Holocene stratigraphic terminology. In Laporte, L. F. (ed.), *Establishment of a Geologic Framework for Paleoanthropology*. Boulder, CO: Geological Society of America. GSA Special Paper 242, pp. 15–22.

Fedoroff, N., and Goldberg, P., 1982. Comparative micromorphology of two Late Pleistocene paleosols (in the Paris Basin). *Catena*, **9**(1–2), 227–251.

Ferring, C. R., 2001. Geoarchaeology in alluvial landscapes. In Goldberg, P., Holliday, V. T., and Ferring, C. R. (eds.), *Earth Sciences and Archaeology*. New York: Kluwer Academic/Plenum, pp. 77–106.

Goldberg, P., 1986. Late quaternary environmental history of the southern Levant. *Geoarchaeology*, **1**(3), 225–244.

Hedberg, H. D., (ed.), 1976. *International Stratigraphic Guide: A Guide to Stratigraphic Classification, Terminology, and Procedure*. International Subcommission on Stratigraphic Classification of the International Union of Geological Sciences. New York: Wiley.

Hester, T. R., Shafer, H. J., and Feder, K. L., 1997. *Field Methods in Archaeology*, 7th edn. Mountain View, CA: Mayfield Publishing Company.

Holliday, V. T., 2004. *Soils in Archaeological Research*. New York: Oxford University Press.

Kemp, R. A., 1986. Pre-Flandrian Quaternary soils and pedogenic processes in Britain. In Wright, V. P. (ed.), *Paleosols: Their Recognition and Interpretation*. Princeton: Princeton University Press, pp. 242–262.

Kemp, R. A., 1999. Soil micromorphology as a technique for reconstructing palaeoenvironmental change. In Singhvi, A. K., and Derbyshire, E. (eds.), *Paleoenvironmental Reconstruction in Arid Lands*. New Delhi: Oxford and IBH Publishing Co., pp. 41–71.

Krumbein, W. C., and Sloss, L. L., 1963. *Stratigraphy and Sedimentation*, 2nd edn. San Francisco: W. H. Freeman.

Labeyrie, L., Skinner, L., and Cortijo, E., 2013. Paleoclimate reconstruction | Sub-Milankovitch (DO/Heinrich) events. In Elias, S. C. (ed.), *Encyclopedia of Quaternary Science*, 2nd edn. Amsterdam: Elsevier, pp. 200–208.

Mandel, R., 1995. Geomorphic controls of the archaic record in the central plains of the United States. In Bettis, E. A., III (ed.), *Archaeological Geology of the Archaic Period in North America*. Boulder, CO: Geological Society of America. GSA Special Paper 297, pp. 37–66.

Mead, J. I., 2013. Vertebrate records | late pleistocene of North America. In Elias, S. C. (ed.), *Encyclopedia of Quaternary Science*, 2nd edn. Amsterdam: Elsevier, pp. 673–679.

NACSN (North American Commission on Stratigraphic Nomenclature), 2005. North American stratigraphic code. *American Association of Petroleum Geologists Bulletin*, **89**(11), 1547–1591.

Pettijohn, F. J., 1975. *Sedimentary Rocks*, 3rd edn. New York: Harper & Row.

Pillans, B., 2013. Chronostratigraphy. In Elias, S. C. (ed.), *Encyclopedia of Quaternary Science*, 2nd edn. Amsterdam: Elsevier, pp. 215–220.

Rose, J., Boardman, J., Kemp, R. A., and Whitman, C. A., 1985. Palaeosols and the interpretation of the British Quaternary stratigraphy. In Richards, K. S., Arnett, R. R., and Ellis, S. (eds.), *Geomorphology and Soils*. London: Allen & Unwin, pp. 348–375.

Schoch, R. M., 1989. *Stratigraphy: Principles and Methods*. New York: Van Nostrand Reinhold.

Stein, J. K., and Linse, A. R. (eds.), 1993. *Effects of Scale on Archaeological and Geoscientific Perspectives*. Boulder, CO: Geological Society of America. GSA Special Paper 283.

Thomas, D. H., 1998. *Archaeology*, 3rd edn. Ft. Worth: Harcourt College Publishers.

Vita-Finzi, C., 1973. *Recent Earth History*. London: Macmillan.

Waters, M. R., 1992. *Principles of Geoarchaeology: A North American Perspective*. Tucson: University of Arizona Press.

Webb, S. D., Graham, R. W., Barnosky, A. D., Bell, C. J., Franz, R., Hadly, E. A., Lundelius, E. L., Jr., McDonald, H., Martin, R. A., and Semken, H. A., Jr., 2004. Vertebrate paleontology. In Gillespie, A. R., Porter, S. C., and Atwater, B. F. (eds.), *The Quaternary Period in the United States*. Amsterdam: Elsevier. Developments in Quaternary Science, Vol. 1, pp. 519–538.

STRONTIUM ISOTOPES

James H. Burton
Department of Anthropology, University of Wisconsin, Madison, WI, USA

Definition

Isotopes: Atoms of the same element that can differ in their weights by having a different number of neutrons in the nucleus.

Introduction

In archaeology, strontium isotope studies are primarily applied to human teeth to identify immigrants and study human mobility. The method has also been used in attempts to determine the provenience of other materials such as wooden beams, maize, wool, glass, and pottery; these exercises have achieved varying degrees of success depending upon the effects of contamination and the intrinsic isotopic variability in geologic materials.

The use of strontium isotopes to study human mobility was first proposed by Jonathon Ericson (1985), who noted the geographic variation in the stable isotopes of $^{87}Sr/^{86}Sr$ and the fact that this ratio is maintained essentially unchanged in the human skeleton from its value in the local environment with no apparent changes imposed by metabolism. When dental enamel develops during the first few years of life, teeth trap this local ratio and keep it unchanged into adulthood and after death. By comparing the $^{87}Sr/^{86}Sr$ in teeth to that of the local ratio, one can identify individuals whose teeth have different ratios and thus who must have experienced childhood in a region with this different $^{87}Sr/^{86}Sr$.

Strontium isotopes

Atoms have different atomic weights, depending upon the number of protons and neutrons in the atom's nucleus. The number of protons defines what element the atom is, i.e., its chemical behavior. The number of neutrons does not affect the identity of an element but nonetheless affects its weight. Strontium atoms are those having 38 protons in the nucleus. They may also have from 46 to 50 neutrons, and thus, strontium atoms can possess a range of atomic weights, 84, 86, 87, and 88, depending upon the number of neutrons. The natural abundances of these isotopes are 0.56 %, 9.86 %, 7.0 %, and 82.58 %, respectively. There is also a radioactive isotope, ^{90}Sr, with 52 neutrons, but this is not a natural isotope and is not relevant here.

Strontium is an alkaline-earth element and behaves much like calcium in its chemistry. It is therefore abundant in calcium-rich rocks such as limestone and also in calcified tissues (bones and teeth). The abundances of its stable isotopes vary geographically because one of the isotopes, ^{87}Sr, is generated by the decay of a radioactive isotope of rubidium, ^{87}Rb. Rubidium is chemically similar to potassium and is common in potassium-rich minerals such as micas (e.g., muscovite), hornblende, and some clay minerals. ^{87}Rb has a half-life of 49 billion years, which means that rocks containing a lot of rubidium (i.e., potassium-rich rocks such as granite, schist, and shale) and that are very old will have accumulated more ^{87}Sr from the decay of ^{87}Rb than young, low-rubidium rocks would accumulate. Thus, the amount of ^{87}Sr varies geographically depending upon the local rock types.

Rocks also vary in ^{87}Sr simply because they have more or less strontium than other rocks, and so isotope chemists compensate for this by dividing the amount of ^{87}Sr by one of the non-radiogenic isotopes. By convention, ^{86}Sr is used because it is similar in natural abundance; ^{87}Sr is about 70 % as abundant as ^{86}Sr, i.e., $^{87}Sr/^{86}Sr \approx 0.7$. The average value of the ratio of ^{87}Sr/^{86}Sr for rocks exposed at the earth's surface is 0.709, and most rocks have ratios fairly close to this average (0.704–0.716). This difference of 0.012 seems small, but it is quite large compared to local variations in the ratio of strontium in once-living organisms, which is typically on the order of ± 0.0002, a quantity that is nonetheless readily measured with modern instrumentation.

Because the half-life of ^{87}Rb is so long, tens of billions of years, the ^{87}Sr/^{86}Sr ratio does not vary within the much shorter time scales of human history or prehistory. Also, because both isotopes are the same element and the atomic weights are so close, the ratio is essentially unaffected by chemical processes such as those involved in human metabolism. The ^{87}Sr/^{86}Sr ratio in bones and teeth is thus that of the local, "biologically available strontium" (see below). Although teeth retain the ^{87}Sr/^{86}Sr ratio of the place of birth, bones continuously remodel themselves chemically, so that if an individual moves, the bones accumulate some strontium from the new location as well. Therefore, the strontium ratio found in teeth reflects the locality of birth and early childhood, whereas that of the bone tends to represent the habitat of later adulthood prior to death. Bones generally continue to accumulate strontium postmortem, so they are not as useful in mobility studies, except in cases where they might provide clues to the ratio at the place of burial.

Local ^{87}Sr/^{86}Sr ratio

In order to apply this technique to humans successfully, we need to know not only the isotope ratio in the enamel of the individual in question but also the ratio in the local environment. Early studies (e.g., Price et al., 1994a; Price et al., 1994b) compared the analytic results from enamel to the ^{87}Sr/^{86}Sr ratio measured in a bone sample from the same individual, which was presumed to approximate the ratio where the individual last lived and likewise was presumed to be the place of death. If the two measurements differed, then the individual could be recognized as an immigrant. However, due to problems of bone contamination, as well as the possibility that a person did not live in the location where he or she died (e.g., in sacrificial burials or reburials), researchers began measuring calcified tissues of local faunal samples and other biological materials. One has to be careful, however, about contamination of ancient faunal bones. Likewise, modern fauna might have different ratios because of access to imported human foods, application of imported fertilizers, or other chronological changes in the landscape such as shifting river courses. Enamel ^{87}Sr/^{86}Sr measurements from ancient humans believed to be local have also been used to assess the local ratio. Although this might seem to be a circular approach, in the absence of evidence of mass immigration, the most commonly observed ratio is parsimoniously that of local individuals, and, in practice, such a sharply defined mode is often found (Burton and Price, 2013). Ideally, several of these methods can be used together to determine a reliable range for the local ratio.

The problem with using geological materials (local rocks and soils) themselves to establish a local isotope ratio is that they generally exhibit ratios with enormously greater ranges than those taken from biological samples (Price et al., 2002). Rocks contain many minerals, each of which possesses its own Rb content, and over the course of its exposure and weathering, each mineral erodes at a different rate. These variabilities make it nearly impossible to determine useful environmental ratios directly from the geosphere. Likewise, geological maps and published ^{87}Sr/^{86}Sr data from geological materials, although useful in planning stages for projects, provide only approximate estimates as to what actual ^{87}Sr/^{86}Sr ratios might be.

Method

Applying the strontium isotope method requires a sample of dental enamel weighing approximately 5 mg and a mass spectrometer capable of high-precision measurements with at least five significant figures. Common quadrupole mass spectrometers and single-collector inductively coupled plasma mass spectrometers (ICP-MS) lack sufficient precision. Normally, either a thermal ionization mass spectrometer (TIMS) or an ICP-MS with multiple collectors (MC-ICP-MS) is required for adequate precision. Cost of analysis is relatively high; at this time, laboratories charge in the range of $100–300 per sample. The result of such an analysis will be the $^{87}Sr/^{86}Sr$ ratio of the material reported with five or six significant digits, e.g., 0.708341, and a measure of uncertainty, which is usually negligibly small (e.g., ±0.0000023).

Case study

As an example of the use of $^{87}Sr/^{86}Sr$ ratios to identify immigrants, Buikstra et al. (2004) analyzed teeth from the Maya site, Copan, including teeth of K'inich Yax K'uk' Mo', the founder of a dynasty that included 15 sequential rulers. Architectural and other evidence suggested that K'inich Yax K'uk' Mo' might have come from Teotihuacan, a contemporaneous power center far to the west, though others thought he could be a local individual who was just adopting the Teotihuacan symbols of power to reinforce his own authority. Buikstra and others measured both human bone and teeth from Copan as well as modern fauna to determine the local $^{87}Sr/^{86}Sr$ ratio of 0.7068 ± 0.0003. Earlier, Price et al. (2000) had done a study of Teotihuacan and surrounding areas and determined a local range there of 0.70463 ± 0.00005, significantly lower than the ratios obtained from Copan. Dental enamel of K'inich Yax K'uk' Mo', in contrast to both of these $^{87}Sr/^{86}Sr$ ranges, yielded 0.7084, indicating unequivocally that K'inich Yax K'uk' Mo' was from neither location.

Other studies (Hodell et al., 2004; Price et al., 2008) show that Mesoamerica can be divided into about eight isotopically distinct regions and that the only region matching K'inich Yax K'uk' Mo's ratio was the Yucatan lowlands north of Tikal, which the authors concluded was his birthplace. This study is unusual in its having been able to constrain the place of origin so narrowly, and this was possible only because baseline data had already been compiled for regions throughout Mesoamerica.

Other applications and future research

Although studies of human mobility remain the principal application of $^{87}Sr/^{86}Sr$, an increasing diversity of target materials beyond teeth and bones is also being analyzed in efforts to determine geographic origins. $^{87}Sr/^{86}Sr$ ratios are now commonly being applied to other species (e.g., van der Merwe et al., 1990; Koch et al., 1992; Hoppe et al., 1999). The rapidly growing teeth of some species such as horse, goat, sheep, and cattle (species exhibiting hypsodonty) additionally can show changes during the development of the tooth, over a span of many months, and this provides a possible window into the detection of seasonal mobility. Other biological materials being investigated include animal fibers in prehistoric clothing (Frei et al., 2009), prehistoric maize (Benson et al., 2009), prehistoric construction timbers (Reynolds et al., 2005), and marijuana (West et al., 2009).

Although minerals and geologic materials generally reveal too much local $^{87}Sr/^{86}Sr$ variation for the method to be applicable, there has been some success in determining the sources of archaeological glass in cases in which the principal source of strontium is a single material such as natron or plant ash (Freestone et al., 2003), especially when augmented by other isotope systems (Henderson et al., 2005). A caution, however, remains the fact that glass is reusable, and waste shards (or cullet) from widely varied sources were often remelted in later historic periods, thereby mixing the chemical and isotopic signatures of more localized production centers.

In addition to extending the method to a greater range of materials, practical applicability of the method is expanding due to the deliberate creation of regional databases (e.g., Price et al., 2008; Evans et al., 2010). With the existence of such databases, researchers in these areas no longer need to acquire their own expensive and time-consuming background data. The power of the method is also being extended through the integration of strontium isotopes with other isotope systems, such as oxygen and lead (e.g., Price et al., 2007; Turner et al., 2009; Price and Burton, 2010; Wright et al., 2010) as well as with trace-element studies (Burton et al., 2003).

Bibliography

Benson, L. V., Stein, J. R., and Taylor, H. E., 2009. Possible sources of archaeological maize found in Chaco Canyon and Aztec Ruin, New Mexico. *Journal of Archaeological Science*, **36**(2), 387–407.

Buikstra, J. E., Price, T. D., Wright, L. E., and Burton, J. H., 2004. Tombs from the Copan acropolis: a life-history approach. In Bell, E. E., Canuto, M. A., and Sharer, R. J. (eds.), *Understanding Early Classic Copan*. Philadelphia: University of Pennsylvania Museum, pp. 191–212.

Burton, J. H., and Price, T. D., 2013. Seeking the local $^{87}Sr/^{86}Sr$ ratio to determine geographic origins of humans. In Armitage, R. A., and Burton, J. H. (eds.), *Archaeological Chemistry VIII*. Washington, DC: American Chemical Society. ACS Symposium Series, Vol. 1147, pp. 309–320.

Burton, J. H., Price, T. D., Cahue, L., and Wright, L. E., 2003. The use of barium and strontium abundances in human skeletal tissues to determine their geographic origins. *International Journal of Osteoarchaeology*, **13**(1–2), 88–95.

Ericson, J. E., 1985. Strontium isotope characterization in the study of prehistoric human ecology. *Journal of Human Evolution*, **14**(5), 503–514.

Evans, J. A., Montgomery, J., Wildman, G., and Boulton, N., 2010. Spatial variations in biosphere $^{87}Sr/^{86}Sr$ in Britain. *Journal of the Geological Society*, **167**(1), 1–4.

Freestone, I. C., Leslie, K. A., Thirlwall, M., and Gorin-Rosen, Y., 2003. Strontium isotopes in the investigation of early glass production: Byzantine and early Islamic glass from the Near East. *Archaeometry*, **45**(1), 19–32.

Frei, K. M., Frei, R., Mannering, U., Gleba, M., Nosch, M. L., and Lyngstrøm, H., 2009. Provenance of ancient textiles – a pilot study evaluating the strontium isotope system in wool. *Archaeometry*, **51**(2), 252–276.

Henderson, J., Evans, J. A., Sloane, H. J., Leng, M. J., and Doherty, C., 2005. The use of oxygen, strontium and lead isotopes to provenance ancient glasses in the Middle East. *Journal of Archaeological Science*, **32**(5), 665–673.

Hodell, D. A., Quinn, R. L., Brenner, M., and Kamenov, G., 2004. Spatial variation of strontium isotopes ($^{87}Sr/^{86}Sr$) in the Maya region: a tool for tracking ancient human migration. *Journal of Archaeological Science*, **31**(5), 585–600.

Hoppe, K. A., Koch, P. L., Carlson, R. W., and Webb, S. D., 1999. Tracking mammoths and mastodons: reconstruction of migratory behavior using strontium isotope ratios. *Geology*, **27**(5), 439–442.
Koch, P. L., Halliday, A. N., Walter, L. N., Stearley, R. F., Huston, T. J., and Smith, G. R., 1992. Sr isotopic composition of hydroxyapatite from recent and fossil salmon: the record of lifetime migration and diagenesis. *Earth and Planetary Science Letters*, **108**(4), 277–287.
Price, T. D., and Burton, J. H., 2010. Isotopic evidence of the African origins and diet of some early inhabitants of Campeche, Mexico. In Tiesler, V., Zabala, P., and Cucina, A. (eds.), *Natives, Europeans, and Africans in Colonial Campeche: History and Archaeology*. Gainesville: University of Florida Press, pp. 175–193.
Price, T. D., Johnson, C. M., Ezzo, J. A., Ericson, J. A., and Burton, J. H., 1994a. Residential mobility in the prehistoric Southwest United States: a preliminary study using strontium isotope analysis. *Journal of Archaeological Science*, **21**(3), 315–330.
Price, T. D., Grupe, G., and Schröter, P., 1994b. Reconstruction of migration patterns in the Bell Beaker period by stable strontium isotope analysis. *Applied Geochemistry*, **9**(4), 413–417.
Price, T. D., Manzanilla, L., and Middleton, W. D., 2000. Immigration and the ancient city of Teotihuacan in Mexico: a study using strontium isotope ratios in human bone and teeth. *Journal of Archaeological Science*, **27**(10), 903–913.
Price, T. D., Burton, J. H., and Bentley, R. A., 2002. The characterization of biologically available strontium isotope ratios for the study of prehistoric migration. *Archaeometry*, **44**(1), 117–135.
Price, T. D., Burton, J. H., Wright, L. E., White, C. D., and Longstaffe, F., 2007. Victims of sacrifice: isotopic evidence for place of origin. In Tiesler, V., and Cucina, A. (eds.), *New Perspectives on Human Sacrifice and Ritual Body Treatments in Ancient Maya Society*. New York: Springer, pp. 263–292.
Price, T. D., Burton, J. H., Fullagar, P. D., Wright, L. E., Buikstra, J. E., and Tiesler, V., 2008. Strontium isotopes and human mobility in ancient Mesoamerica. *Latin American Antiquity*, **19**(2), 167–180.
Reynolds, A. C., Betancourt, J. L., Quade, J., Patchett, P. J., Dean, J. S., and Stein, J., 2005. $^{87}Sr/^{86}Sr$ sourcing of ponderosa pine used in Anasazi great house construction at Chaco Canyon, New Mexico. *Journal of Archaeological Science*, **32**(7), 1061–1075.
Turner, B. L., Kamenov, G. D., Kingston, J. D., and Armelagos, G. J., 2009. Insights into immigration and social class at Machu Picchu, Peru based on oxygen, strontium, and lead isotopic analysis. *Journal of Archaeological Science*, **36**(2), 317–332.
Van der Merwe, N. J., Lee-Thorp, J. A., Thackeray, J. F., Hall-Martin, A., Krueger, F. J., Coetzee, H., Bell, R. H. V., and Lindeque, M., 1990. Source-area determination of elephant ivory by isotopic analysis. *Nature*, **346**(6286), 744–746.
West, J. B., Hurley, J. M., Dudás, F., and Ehleringer, J. R., 2009. The stable isotope ratios of marijuana. II. Strontium isotopes relate to geographic origin. *Journal of Forensic Sciences*, **54**(6), 1261–1269.
Wright, L. E., Valdés, J. A., Burton, J. H., Price, T. D., and Schwarcz, H. P., 2010. The children of Kaminaljuyu: isotopic insight into diet, status and long distance interaction in Mesoamerica. *Journal of Anthropological Archaeology*, **29**(2), 155–178.

Cross-references

Glass
Inductively Coupled Plasma-Mass Spectrometry (ICP-MS)
Oxygen Isotopes
Paleodiet

SUBMERGED CONTINENTAL SHELF PREHISTORY

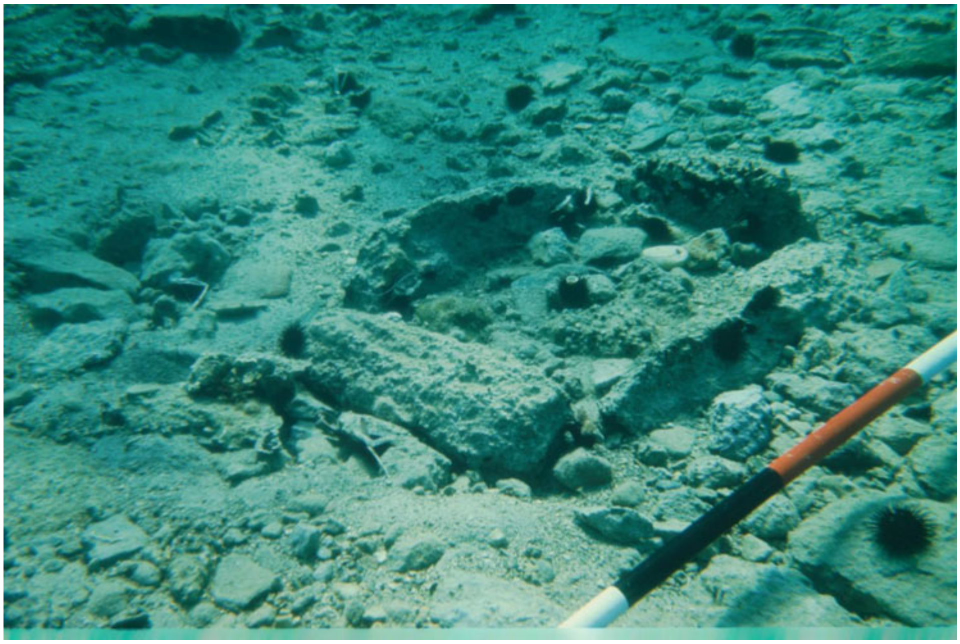
Nic C. Flemming
National Oceanography Centre, University of Southampton, Southampton, Hampshire, UK

Introduction

Over 3,000 submerged prehistoric occupation sites on the continental shelf are known worldwide, varying in depth from the nearshore to about 100 m and ranging in age from 5,000 years to 0.5–1.0 million years. Sites have been found off the coast of every continent except Antarctica. These findings are consistent with the climatic fluctuations of the Pleistocene glacial cycles, the repeated lowering of global sea levels to about −130 m, and the extension of adjacent continental climate, vegetation, freshwater drainage, and fauna onto the exposed continental shelf land surfaces. The inclusion of the prehistoric populations and cultures of the continental shelf into world prehistory has a substantial impact on our understanding of the development of coastal resources, population density and distribution, movements of populations, specialized coastal technologies, diet, and early seafaring. Although submerged sites and submerged Pleistocene terrestrial landscapes have been known for more than 100 years, the ability to search for and work on sites in a systematic way has been possible only in recent decades. Acoustic technology, integrated seabed digital mapping systems, autonomous underwater vehicles (AUVs), diving equipment, and underwater work capability have evolved rapidly to make this possible. International treaties and national heritage legislation in many countries provide protection for seabed prehistoric sites. Most sites found so far are shallower than 10–20 m, with a few deeper than 40 m, and none are in the tropics. The present challenges are to integrate and absorb the significance of known submerged sites; to work in deeper water toward the edge of the shelf in order to detect and examine more sites occupied when sea level was at its lowest during the last glacial maximum; to locate and study submerged sites in the tropics; to integrate the continental shelf data with human genetic indicators of early migrations; and to understand more about how different anthropogenic indicators survive inundation, such as shell middens and occupied caves. The subject is immensely composite, involving all aspects of the seabed earth sciences, research technology, climate change research, paleo-oceanography, and prehistoric archaeology. This entry is a very brief summary.

Background to continental shelf archaeology

The study of prehistoric human and hominin occupation of the continental shelf derives from a simple premise. The logical consequences of this premise are complex, and the task of demonstrating those consequences in practical research and deriving valuable geoarchaeological insights requires the latest understanding and analysis of Pleistocene climate change, sea-level change, and the



Submerged Continental Shelf Prehistory, Figure 1 Cist grave dating from the Middle Bronze Age at a depth of 3 m in the submerged prehistoric town near the islet of Pavlopetri, southern Laconia, Greece. The scale on the colored bar is 25 cm (Photo by N. C. Flemming; see Henderson et al., 2011).

application of modern seabed surveying technology. The premise is that the well-established exposures of the continental shelf down to a depth of about −130 m during glacially controlled low sea levels of the Pleistocene were of sufficient duration for a contemporary terrestrial environment of river drainage, vegetation, and fauna to develop on the shelf during these lowstands, including our hominin ancestors and anatomically modern humans (AMH). On the less fertile desert and polar coasts, the adjacent continental conditions also extended to the exposed shelves, possibly supporting sparse populations suitably adapted. The area of the continental shelf is 5 % of the area of the globe, and this territory would add an area equivalent to that of Africa to the presently existing land area. In archipelago-peninsula regions such as Europe, Southeast Asia, and northern North America, it would add 40–100 % to the present regional land masses, so that this terrain cannot be ignored in our attempts to reconstruct the prehistoric evolution of humans and their diffusion throughout the modern global land areas. Several multi-author edited volumes have attempted to provide an overview of the main issues and the justification for research into these problems, e.g., Allen et al. (1977), Masters and Flemming (1983), Fischer (1995), Flemming (2004a), Yanko-Hombach et al. (2007), Benjamin et al. (2011), Buynevich et al. (2011), Harff and Lüth (2011), Evans et al. (2014), Flemming et al. (2014), and Harff et al. (2015). For a global overview of the origins and development of prehistoric seafaring, which is closely interwoven with questions regarding occupation of the continental shelf, see Anderson et al. (2010).

There are additional contributory technical and scientific subjects on which background understanding is essential to assessing the origins and survival of seabed prehistoric sites. The following review volumes are relevant. For coastal dynamics and the action of waves and currents on deposits in shallow water, see Carter (1993) and Davidson-Arnott (2010); for the structure and surface sediments of the continental shelf in the Quaternary context, see Harff et al. (2007a), Harff et al. (2007b), and Chiocci and Chivas (2014); for a review of Pleistocene climate change, sea-level change, subdisciplines, and techniques, see Shennan et al. (2015).

Human genetic studies have shown in broad terms how different phases of the hominin expansion out of Africa proceeded in successive waves with sequential arrival dates into different continents, and these diagrams of slow migration, usually averaging less than 1 km per year, imply prolonged periods when hominins/humans were living on or slowly traversing the now submerged continental shelf – e.g., Forster (2004), Hill et al. (2007), Pope and Terrell (2008), Soares et al. (2008), and Henn et al. (2012). Genetic data suggest that the successively dispersed groups have sometimes interbred at the margins or overlaps of diffusion zones, but dating based on DNA itself is still subject to revision (Scally and Durbin, 2012). The adaptation of human cultures to coastal and marine exploitation and technologies occurred while the global sea level was many tens of meters lower than it is at present, so that the archaeological deposits recording the processes of that adaptation are now submerged. There is no other way of studying the occupation sites associated with the earliest phases of seafaring and exploitation of marine resources than working underwater (Figure 1).

The following archaeological research themes or objectives for gathering and interpreting data from the continental shelf were listed in Flemming et al. (2014, 42) based on ideas provided by Geoff Bailey. They are modified here to extend the context globally.

1. The attractiveness of coastal regions to human populations is due to their unusual productivity in plant and animal resources, with abundant water supplies, spring lines, coastal meadows and marshes, and sources of raw materials and intertidal mollusks along the shore edge. In some cases, these ancient coastal areas are likely to have presented unique combinations of plant and animal resources with no equivalent analogue on modern coasts, while at the same time being richer than their contemporaneous hinterlands. These attractions are partially demonstrated by caves on the present-day coastline with long archaeological sequences extending back to earlier short-lived episodes of high sea level and situated adjacent to steeply shelving offshore topography or in material being eroded out of ancient coastal and riverine deposits by marine erosion along the modern coast. But the majority of relevant evidence and the key landscapes and paleoenvironments in most areas are likely now submerged and lying on the seabed. On modern desert coasts, it is possible that the effect of subterranean groundwater flow, springs, and flash floods might have provided habitable areas on what is now the outer continental shelf.
2. Closely allied to theme (1), these productive coastal regions are significant as centers of population growth and pathways of population movement and dispersal along continental margins and between land masses during the earliest periods of the Paleolithic era.
3. Nearshore archipelagos are important as “nursery” areas for early experiments in seafaring and maritime economies and also as stepping stones in the coastwise expansion of early populations. This factor is highly relevant in the Mediterranean, the Red Sea, throughout Southeast Asia including early access to Greater Australia, the Caribbean, and into the periglacial and deglaciated regions of the northern continents.
4. Closely allied to theme (3), submerged coastal areas hold clues to the question of the origins of experiments in sea crossings with simple rafts and boats, seal hunting, offshore fishing, and visitation of offshore islands that often offer rich concentrations of nesting birds and marine resources or useful materials such as obsidian.
5. Sea-level changes impose potentially enormous impacts on coastal areas, resulting in alterations to paleogeography and environmental conditions, as well as to the social geography, demography, economic organization, and cultural interaction of ancient populations.
6. The continental shelf holds evidence for a deeper history of coastal sedentism, with year-round settlements, permanent dwellings, and other durable structures and monuments of stone or wood.
7. The significance of coastal regions also lies in providing fertile and cultivable soils and pastures for early farmers globally, as well as serving as pathways for the expansion of farming from the Near East into southern Europe, a process that was underway when sea levels were still considerably lower than the present.
8. There is overriding importance in treating the present-day land surface and the submerged areas of the continental shelf as a seamless whole from the point of view of their prehistoric inhabitants, who are likely to have ranged widely over large territories untrammeled by today’s physical boundaries.

These research themes were matched with a ranked list of objectives in national management of continental shelf prehistoric resources resulting from a survey of national heritage agencies in 13 European countries (Flemming et al., 2014, 40).

Continental shelf prehistoric research, or the process of conducting research into the geoarchaeology of the continental shelf, includes many subcomponents, stages, technologies, and contributory sciences. These can be summarized as follows and will be reviewed later:

1. Determination of site locations in the context of the original landscape and resources when the shelf was exposed as dry land during glacial periods of low sea level
2. The potential for modeling site distribution and possible predictive modeling for site density and survival
3. The terrestrial taphonomy of site survival as well as cultural and noncultural site formation processes before inundation
4. The dynamic geomorphological processes of first marine transgression (when coastal sites are inundated for the first time): transition of the surf zone, degree of erosion or protection afforded by local topography, wind fetch, wave refraction, and lateral sediment transport
5. The effects of multiple marine transgressions and the mechanisms by which prehistoric archaeological sites may survive several glacial cycles of sea-level rise and fall
6. Modern sediment seabed conditions: marine sediment movements, erosion, burial, and processes of site discovery
7. Application of modern oceanographic and commercial acoustic technology to the search for, mapping of, and discovery of submerged prehistoric landscapes and archaeological sites
8. Survey, conservation, monitoring, excavation, and management of seabed prehistoric sites in the context of the UNESCO Convention on the Protection of the Underwater Cultural Heritage

These components will be discussed in a later section, followed by a review of findings and interpretation, and finally by a review of future challenges. Each component is itself complex and can only be summarized here, but the summaries will give documented examples of projects carried out and sites that have survived. The analysis is based on what can be shown to have happened, not a theory as to what should happen.

History of exploration

Chance retrievals of prehistoric artifacts and terrestrial Pleistocene fauna from the seabed were noted repeatedly between 1900 and 1970, and they were correctly understood and interpreted by scholars. An early problem was that individual finds came from different periods, widely different localities, and were out of stratigraphic context so that they were often treated as antiquarian curiosities rather than serious archaeological discoveries.

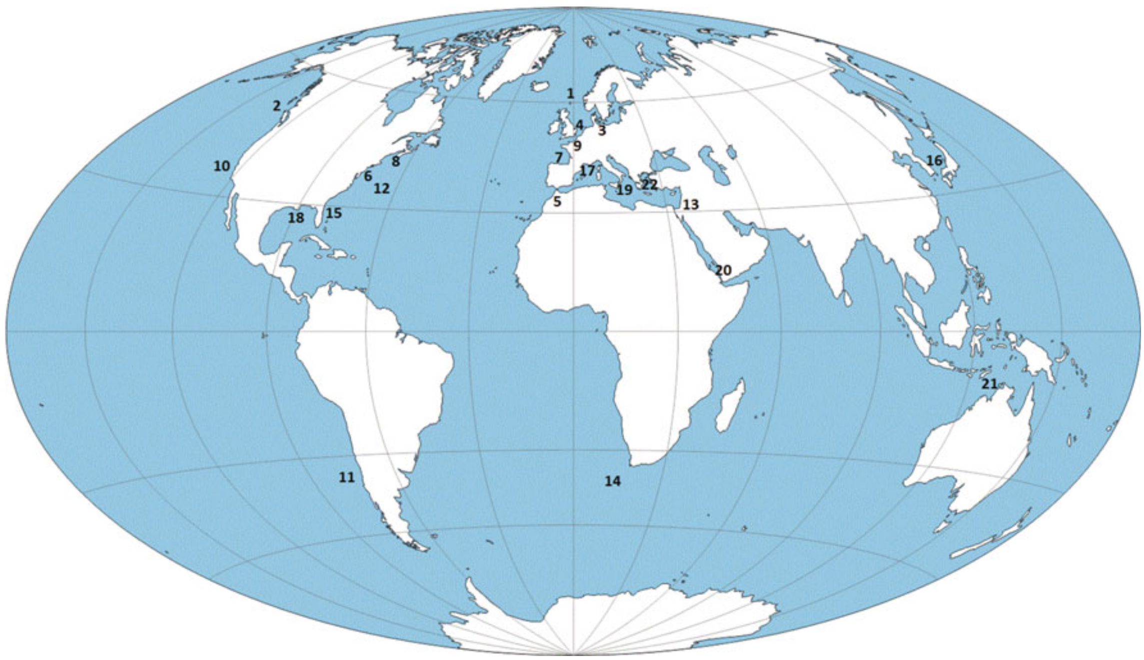
The first realization of the possible human occupation of the continental shelf happened about 1900, and a steady sequence of papers followed from Marcellin Boule (1906) and Clement Reid (1913) through to Burkitt (1932), Blanc (1940), North (1957), Emery and Edwards (1966), Whitmore et al. (1967), Harding et al. (1969), Fladmark (1975), and Clausen et al. (1979). The demonstrable fact that the glacial period shelf had been occupied by Pleistocene fauna and hominins, and that some sites had survived, was established, but motivation from institutions and funding agencies to push the matter further was weak. The lack of support may have been justified on four grounds. First, archaeology had plainly progressed beyond the point of just "finding things." New synthesizing and analytic branches of the subject were growing in academic esteem and influence, often requiring data from many tens or hundreds of stratified and dated sites. These methods could not be applied to the sparse and scattered data from the seabed, where only a few sites were known, and they had been found by chance, so that the subject had an old-fashioned and unsystematic association. Second, the possibility of high-tech scientific search for prehistoric remains on the seabed was still implausible, in spite of the steady advances in acoustics and particularly in side-scan sonar, since no technology from the 1960s to the 1990s could map, survey, or log the data of the seabed with sufficient accuracy to reveal prehistoric sites other than by chance. Third, archaeologists had not formulated intellectual problems or hypotheses that seemed to need data from the continental shelf. Finally, research on the seabed was thought to be expensive, with the constant risk of failing to find worthwhile material. The adjunct to this last point was, paradoxically, the contrasting fact that fishermen, dredgers, and sports divers continued to find and recover more prehistoric artifacts, which, once in their hands, were out of context, even if the recovery was reported quickly to the authorities.

By the late 1980s, enough was known to start systematizing and pointing the way to research strategies. Louwe Kooijmans (1970–1971), Cockerell and Murphy (1978), Ruppé (1978, 1980), Skaarup (1980), Andersen (1980, 1985), Masters and Flemming (1983), Stright (1990), and Galili et al. (1993) collectively showed that there was a definable range of coastal topographies and geomorphological niches within which unconsolidated prehistoric deposits had survived the process of inundation and transition of the surf zone. The key factor required is the near-total protection of the deposit from wave attack either due to prior burial or to protection with an extremely limited wind fetch and wave diffraction or refraction by local topography. Barrier sand islands, calcified dune ridges, lagoons, peat bogs, beach ridges, rias, fjords, estuaries, marshes, wetlands, sinkholes, caves, rock outcrops and ridges, nearshore islands, close-spaced archipelagos, accumulative beaches, river meanders, and sediment progradation and deltas can protect and preserve prehistoric sites during inundation, and evidence shows that they have done so.

The precise topography and combination of bedrock forms and overlying sediments needed to provide protection are quite local and thus have to be measured with an accuracy of a few meters. Geomorphological structures need to be resolved substantially below the 1 km level and preferably below the 10 m level adjacent to the site. As with prehistoric sites on land, most deposits are destroyed by natural processes, but it is possible to identify a range of topographic circumstances that will protect archaeological deposits from destruction by the rising sea. No published charts or standard surveying technique available during the 1960s to 1990s could approach the resolution required.

By the early 2000s, with multibeam sonar, sector scanning, and other technologies becoming available at modest cost, the subject was ready to take off with new vigor. The work of Long et al. (1986), Scuvée and Verague (1988), Crock et al. (1993), Hayashida (1993), Fischer (1995), Clottes and Courtin (1996), Josenhans et al. (1997), Fedje and Josenhans (2000), Werz and Flemming (2001), and Faught (2004) confirmed that prehistoric sites could be found off the shores of nearly every continent (Figure 2) and that some sites had survived multiple glacial cycles with repeated marine transgressions.

A conference was held to review the accumulated finds from the North Sea (Flemming, 2004a), and a European coordinated project was launched in 2008. The SPLASHCOS (Submerged Prehistoric Archaeology and Landscapes of the Continental Shelf) project, 2008–2013, centralized a catalogue of over 2,500 submerged prehistoric sites in European seas (Figure 3) (Jöns et al. 2016), and it is now possible to analyze that database to show the distribution of surviving sites with their age and water depth. These data indicate that most recorded sites are from the last inundation of the shelf with its maximum at about 20,000 years BP, but a small number survive from previous glacial cycles.



Submerged Continental Shelf Prehistory, Figure 2 A selected sample of sites with submerged prehistoric materials or submerged terrestrial landscapes that have been well mapped to locate sites: (1) Orkney coast and Viking Bank; (2) British Columbia; (3) South West Baltic (over 1,500 sites); (4) North Sea (many tens of sites and thousands of paleontological retrievals); (5) Gorham's Cave, Gibraltar; (6) Chesapeake Bay; (7) Morbihan Bay, France; (8) Maine coast (Native American lithics offshore); (9) Fermanville, France; (10) California; (11) Quintero Bay, Chile; (12) Delaware offshore ("Cinmar" lithic); (13) Israeli Mediterranean coast (submerged Mesolithic villages); (14) Table Bay (Acheulean hand axes); (15) Cape Canaveral beach (Paleoindian site); (16) Tokonami River Bay (Jomon site); (17) Grotte Cosquer (cave paintings); (18) Florida coast, Gulf of Mexico; (19) Sicily (submerged Bronze Age tombs); (20) Farasan Islands, Red Sea; (21) Cootamundra Shoals, Australian shelf; (22) Aegean (Agios Petros and Pavlopetri).

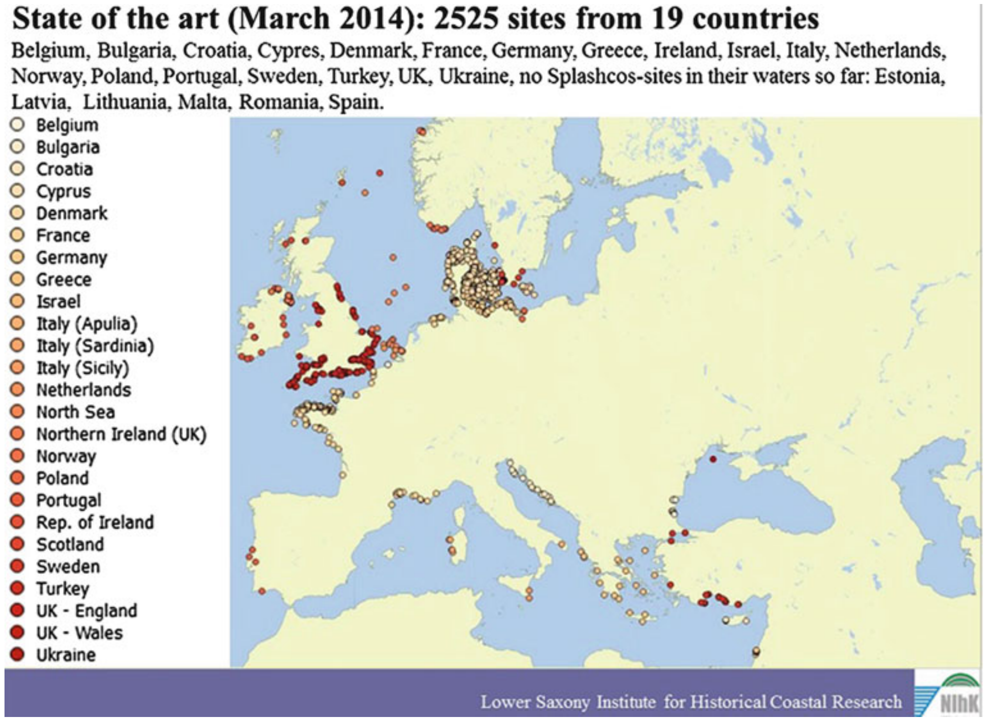
The European Marine Board subsequently commissioned a multiagency report on possible future research on submerged prehistoric landscapes in European seas (Flemming et al., 2014).

Sea-level change and climate

Pleistocene sea-level changes led to repeated exposures of seabed to a depth of 135–150 m, and this area coincides more or less with the geological definition of the continental shelf (Chiocci and Chivas, 2014). There are numerous estimates and models of the global change in sea-level surface through time for the last half million years (e.g., Figure 4). Each local relative sea-level curve through time will depend upon the accumulated effect of the global ice volume extracted from the sea and transferred onto the land as ice sheets, combined with the response of the earth's crust to that transfer of mass – the so-called glacial-hydro-isostatic adjustment (GIA) – and local tectonic earth movements (e.g., Lambeck and Purcell, 2005; Peltier and Fairbanks, 2006; Rohling et al., 2009; Stanford et al., 2011; Lambeck et al., 2014; Shennan et al., 2015).

Although many landscape features are eroded during marine transgression or buried in subsequent deposits of marine and deltaic sediments, many features can be preserved in different environments. There are river valleys, cliffs, moraines, ice tunnels, frost-shattered slopes, screes, marshes, coral reefs, drowned forests of tree stumps, fallen tree trunks, fossil mangrove forests, fossil dunes, beach terraces, beachrock, karstic caves and sinkholes (Figure 5), and many other features of the terrestrial landscape buried under the sea.

These features seldom show up on charts and seabed maps because the mapping process and sampling of depth soundings smooth out abrupt changes in gradient. Submerged cliffs do not appear on navigation charts. The software for digital terrain modeling often makes matters worse by statistical smoothing, although algorithms can be applied to the raw data to detect abrupt features. However, divers, submariners, and fishermen with good echo sounders have always known about abrupt vertical relief on the seabed, and the modern techniques of multibeam sonar can now show the true complexity of the continental shelf landscape (Figures 5 and 6). The main features that have showed up easily on major charts in the past have been (1) the big river valleys and glacial scour valleys which cut broad depressions across the shelf toward the continental margin and the deep ocean, (2) the canyons, and (3) the eroded flatness of terraces formed by coastal marine abrasion under some conditions. Now, smaller



Submerged Continental Shelf Prehistory, Figure 3 Distribution map of submerged and intertidal prehistoric sites in European and northern Mediterranean coastal seas. Data compiled by Hauke Jöns for the European research framework SPLASHCOS COST Action TD0902 "Submerged Prehistoric Archaeology and Landscapes of the Continental Shelf." Most recorded sites are shallower than 10 m depth, but some lie in the range of 20–40 m and a few deeper.

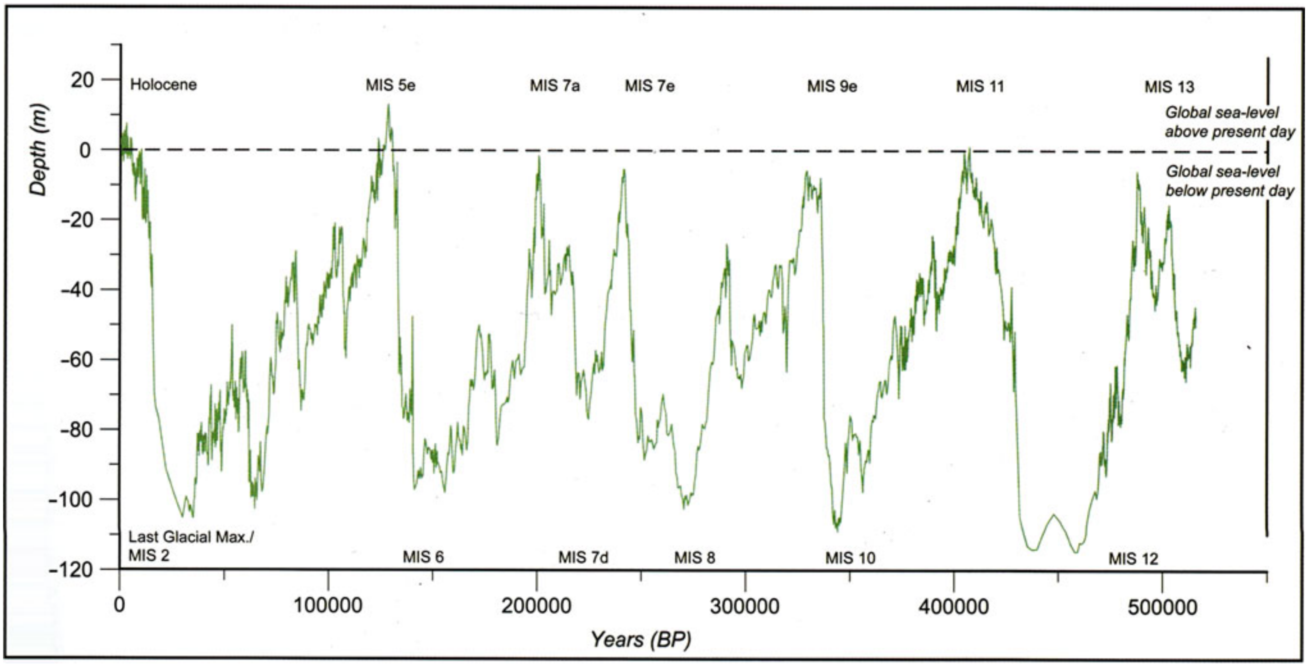
geomorphological features are being added, down to scales of a few meters.

The complexity of global sea-level changes during the Pleistocene, the relatively high frequency events and oscillations with periodicities on the order of 1,000 years, and the distinct differences in details between successive major cycles are now being worked out. From an archaeological perspective, the attention being given to the penultimate glacial cycle overlaps with the critical periods of some early migrations into Europe and Southeast Asia. The rise of sea level toward the last interglacial highstand about 125,000 years ago has been analyzed by Marino et al. (2015).

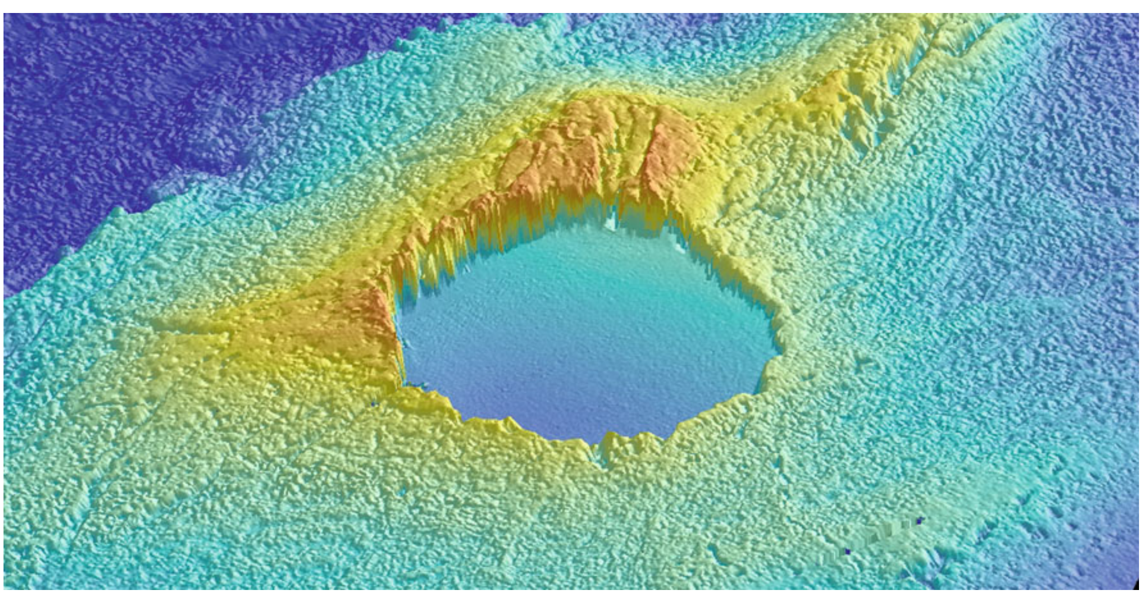
Geoarchaeological components of prehistoric site research on the continental shelf

Determination of site location in the context of the original landscape and resources of an exposed shelf during glacial stages of low sea level

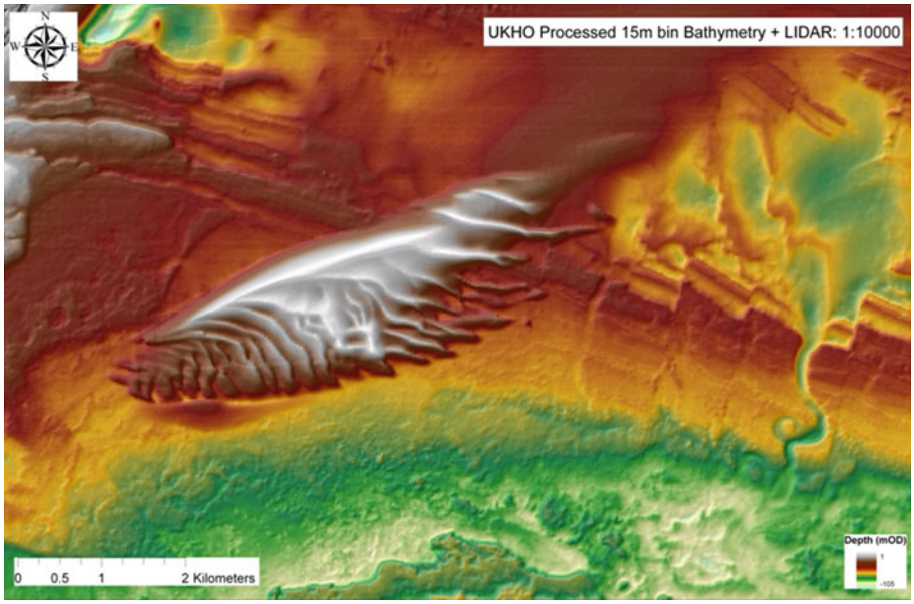
During the last million years, the continental shelf was exposed and completely dry about six times, and for about half of the last million years, the continental shelf has been exposed over about half of its total area (Figure 4). These cycles were driven by the glacial-deglacial cycle of the continental ice caps with a periodicity of approximately 125,000 years, and each cycle was accompanied by shifts in climatic zones, rainfall, and vegetation. During the same period, early hominins evolved from the simpler species (*Homo ergaster*, *Homo erectus*, *Homo heidelbergensis*) through Neanderthal and *Homo sapiens* (see, e.g., Klein, 2009; Fu et al., 2014). The evolution and distribution of hominins was constrained by the geography and climate during each period and by the sea level. The topographic features which welcomed or constrained coastal dwelling and migrations (Westley and Dix, 2006) are now under the sea, as are the sedimentary traces of the environments in which people lived (Bailey and Flemming, 2008; Flemming et al., 2012). Analysis to reconstruct the shelf landscape upon which people lived and through which people would have migrated between the Middle East and Southeast Asia has been carried out by Bulbeck (2007, 315–321) and Erlandsen and Braje (2015), illustrating the very complex and variable landscapes and terrains that would have been encountered. In contrast, Dixon and Monteleone (2014) use seabed data and paleontological and archaeological findings to examine the submerged prehistoric landscape of Beringia. Erlandson et al. (2015) examine the extent to which marine coastal resources facilitated the modern human migration from Northeast Asia to the Americas.



Submerged Continental Shelf Prehistory, Figure 4 Global sea-level curve for the last half million years, showing principal fluctuations within the main glacial cycles. The local relative sea-level change at any point on the coast is altered by the additional regional response to the transfer of mass between land-based ice and the ocean and local tectonics (Based on Rohling et al., 2009, with permission).



Submerged Continental Shelf Prehistory, Figure 5 3D multibeam image of a submerged karstic sinkhole or doline off the coast of Malta. Diameter is 270 m and depth is 11–12 m (From Micallef et al., 2013, with permission).



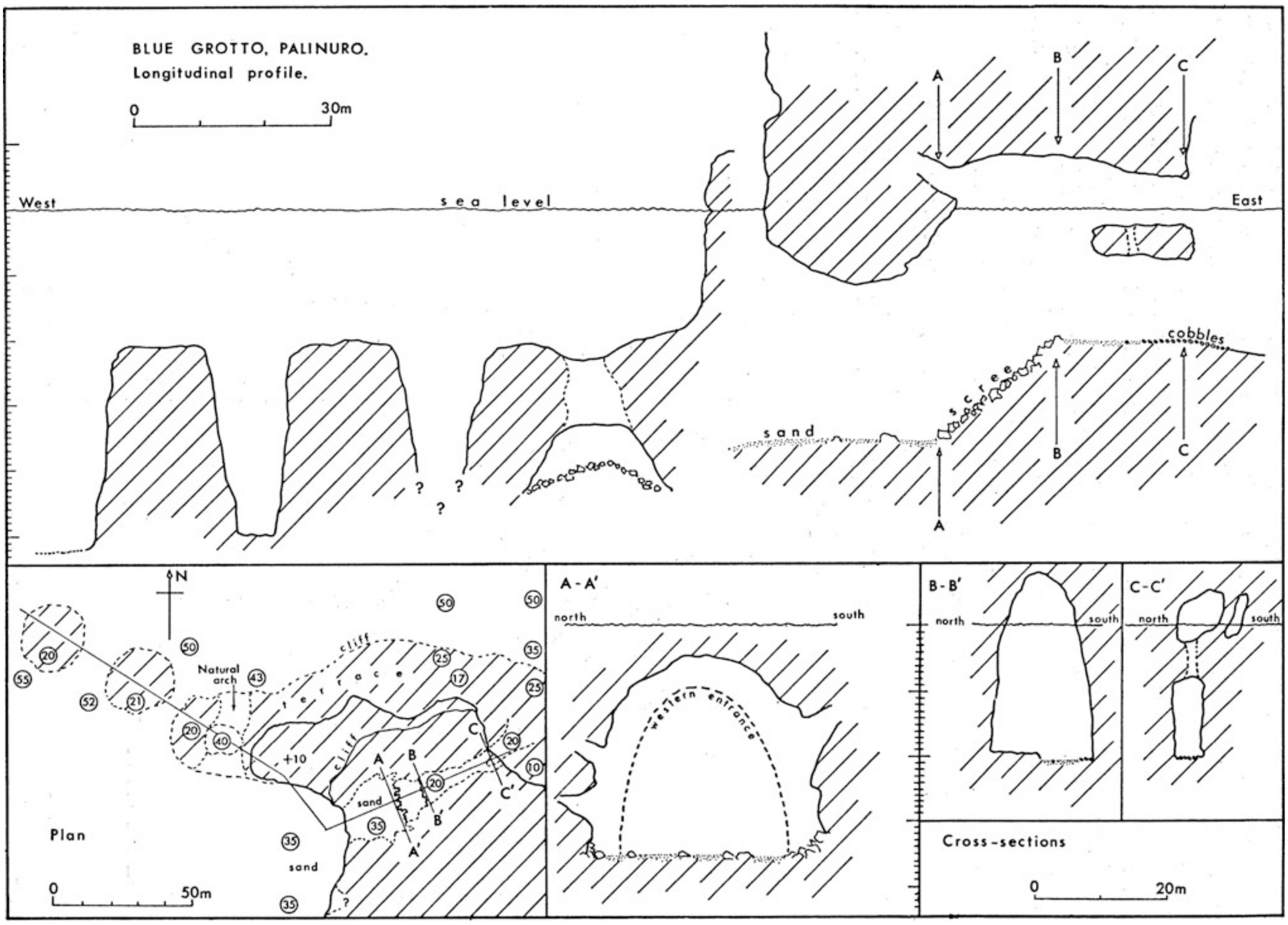
Submerged Continental Shelf Prehistory, Figure 6 Seabed geomorphology in Portland Bay, south coast of England. The shallow sand banks show white, with a sinuous dynamic structure. They overly bedrock with the dipping strata showing rectilinear features, with offset faults. To the east side, an incised river valley cuts through the bedrock and includes an isolated oxbow lake (small circular feature, *lower right*) (Image from Justin Dix, with permission).

The science of detecting or locating the most probable position at which hominins lived or settled, leaving stratified deposits, at different past periods and in widely different climatic and topographic environments is too vast even to be summarized here. There are two chains of logic: the first one positing that determining probable site locations on the shelf should assume that the culture and foraging system on the formerly exposed shelf was the same as that for known equivalent sites explored on present land surfaces and the second one making the assumption that proximity to the coast, or a manifestly different type of terrain now submerged, resulted in different cultural and technological habits.

As on land, offshore prehistoric sites dating from successive glacial stages can be found scattered over the same area, so that sites of widely different dates may be located in proximity or even superimposed. The limiting factor is that no sites were occupied in the time period when that location was submerged. For the Lower Paleolithic, it is reasonable to assume that the effect of proximity to the coast had minimal effect other than the fertility of the coastal plains themselves, although it is not impossible to imagine very primitive rafts of reeds or bamboo being used. Thus, site location is likely to be determined by the fertility, relief, and roughness factors analyzed by King and Bailey (2006) and Bailey and King (2011). The earliest dates for consumption of freshwater mollusks and their use as tools with engraved decorations are more than one million years ago (Joordens et al., 2015), and it is reasonable that people would have exploited marine mollusks from time to time at similar dates. Bednarik (2003) proposes that hominins could construct simple rafts to cross between islands of the Indonesian archipelago more than 0.5 million years ago. For a general history of early seafaring and exploitation of marine resources, see Anderson et al. (2010).

As the skill at exploiting coastal, shoreline, and shallow water resources increased – albeit at a rate that is still under discussion and varying greatly between regions – we can assume that the cultural patterns and technologies possessed by hominins living close to the shoreline, and on the adjacent coastal hinterland, became progressively marine oriented and less like the settlement patterns and hunting-foraging strategies of groups living farther inland or at distances of many hundreds of kilometers from the sea. Most submerged sites studied so far would have been occupied in sheltered locations, either close to the shore or inland, but in open positions, not inside caves.

Coastal caves and shell middens have attracted special attention, research, and debate. Prehistoric shell middens are known in the tens of thousands, globally distributed from Portugal and Denmark to California, Japan, Australia, and many other countries. A large shell mound can contain thousands of tons of shell debris, together with other food remains, charcoal, and tools. The largest middens date from 8 to 7 ka BP (Bailey and Flemming, 2008), but smaller shell deposits have been found associated with caves close to the present shoreline dating from the last interglacial around 125 ka BP (Bailey and Flemming, 2008) and even earlier. The deduction is that



Submerged Continental Shelf Prehistory, Figure 7 Blue Grotto cave, Capo Palinuro, Italy. Plan and profile sections with no vertical exaggeration. The cave penetrates the headland with a floor level at −20 m and then descends with a rubble scree to −50 m, where there are two outlying pinnacles and a natural rock arch, all adapted to a paleo-shoreline wave erosion level at −50 m (Flemming, 1968).

mollusks were a consistent, though possibly minor, component of diet in the coastal zone throughout the last glacial cycle and that most of this food was consumed on the shelf and the shells discarded below present sea level. However, searches for concentrated midden deposits offshore have been problematic, as wave action seems to destroy and scatter the shells even in the most sheltered locations. Faught (2014, 43–44) discusses the problem, and there have been numerous projects to find middens offshore in regions where they are very common on the present shoreline (e.g., Bailey et al., 2015). Negative results seldom appear in the literature, but it is manifest that this problem needs intensive research to evaluate the discrepancy. Faught (2014, 44) describes a suspected drowned midden within a river bed, and shell accumulations are known in muddy deposits in the Baltic, suggesting that a cohesive matrix of sediment or vegetation is needed to preserve a shell midden from wave attack. The present author has observed a shell midden collapsing slowly into the water at Little Swanport, Tasmania, under the influence of waves only a few cm in height. The question remains as to whether a scattered midden would still present a trace distinguishable from a natural shell bed, and this has long been a concern (Gagliano et al., 1982).

Large caves on land are the quintessential location for Paleolithic accumulations of massive deposits, and the search for occupied caves below sea level started in earnest already in the 1950s and 1960s (Figure 7). Caves close to or on the modern beach such as Gorham's Cave, Gibraltar (Carrión et al., 2008; Stringer et al., 2008; Rodríguez-Vidal et al., 2014), and the South African coastal caves at Eland's Bay, Blombos Cave, and Klasies River Mouth typify a sequence containing sparse evidence for the use of marine resources at the last interglacial, with the reappearance of evidence for a marine diet including mollusks, fish, seabirds, and mammals within the last 20 ka. The cave on the Turkish coast at Üçağızlı (Kuhn et al., 2009) provides another example of an occupied Paleolithic cave within a few meters of the present shore. Minor terrestrial deposits with a few bones or worked lithics have been found in a few submerged caves on the coast of France and Italy, but the only discovery of significance has been the so-called Grotte Cosquer (Clottes and Courtin, 1996; Clottes et al., 2005; Collina-Girard, 2005). In this case, a 150-m-long tunnel which has its entrance 40 m below sea level emerges inside a flooded cave above present sea level, on the walls of which there are Paleolithic paintings, dating from 27 to 19 ka BP. This configuration is so curious that nothing like it has been discovered in the last 25 years of searching.

Prehistoric remains have been found in karstic sinkholes, or dolines, on land (e.g., Clausen et al., 1979), but the lack of substantial stratified deposits found in submerged sea caves, in spite of thousands of caves being mapped by speleologists, has been discussed by Antonioli in a section of the report by Flemming et al. (2014, 83). As with middens, the lack of progress does not usually find its way into publications, but the problem needs a renewed level of analysis to identify the reasons and possibly develop a new exploration and probing strategy.

In summary, there are still many problems to be solved regarding site location and discovery, but there is ample field evidence that prehistoric hominins and AMH occupied the exposed continental shelf at many periods and in different parts of the world, in different landscapes, and that large parts of the submerged landscape can be mapped and interpreted so as to reconstruct the living environment and place the sites in context.

The potential for modeling of site distribution and possible predictive modeling for site density and survival

The former occupation pattern on large exposed areas of the shelf can be approximated first by the known contemporaneous population density and site characteristics of the adjacent land mass above present sea level. This is only an approximation, since the climate would have been milder at a lower level closer to the sea, freshwater drainage and reduced gradients may have produced springs (Faure et al., 2002) and increased vegetation or marshlands, and the population itself may have adapted in special ways to the coastal and marine environment and ecosystem. Nevertheless, the existence of cave sites, rock-shelters, and open ground low gradient sites, or – at later periods – built structures of wood, stone, and bone, should be very broadly comparable, taking into account the topographic and geologic data available from the seabed.

Because of the high cost of modern technical searching of the seabed, including the costs of ship time, it has been an ideal goal since the 1980s to use computer modeling to relate probable site occurrence to the mapped submerged landscape so as to increase the probability of finding sites on the seabed for research or protection. As an accurate site predictive system, this has been an unachievable goal. Nevertheless, modeling serves several uses:

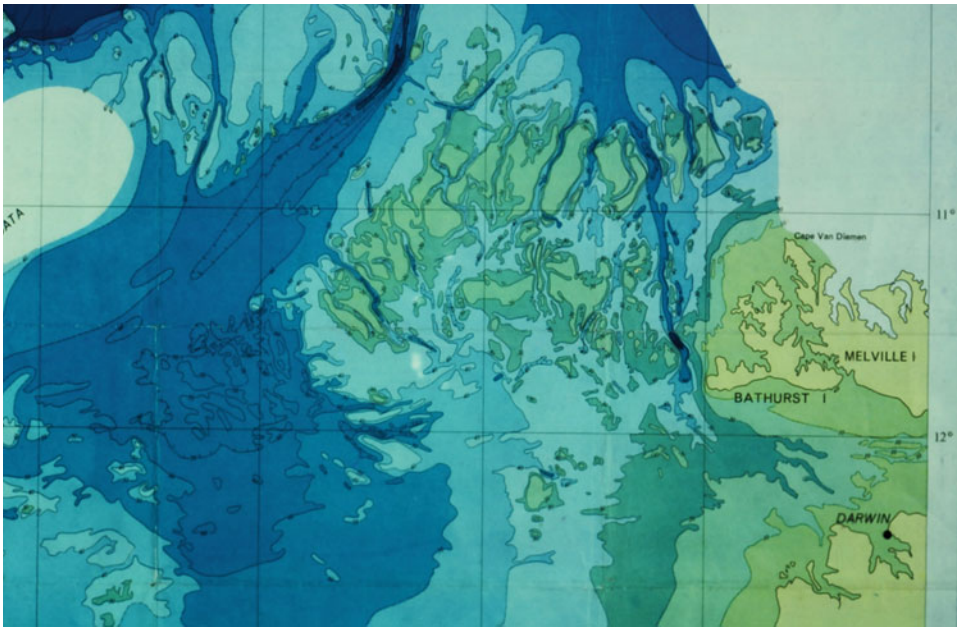
1. To estimate probable original overall site spatial density
2. To interpolate between known sites to reinforce models, calibrate models, and fill gaps
3. To estimate the probability of site occurrence for heritage management, research, and protection, ultimately to grade areas as low or high probability

The extrapolation of known site density from the land to offshore may be based on an assessment of site survival rates on land, but this is usually unknown for the seabed. In effect, as some sites are found offshore, the number that have survived, or have been found, provide by comparison an indication of the number that have probably been lost or buried.

When a few submerged sites have been found, and assuming that they are contemporaneous one with another, it becomes possible to draw parallels with equivalent cultures and landscapes that have already been studied, including the apparent relationship between sites and immediate environmental constraints. Thus, an iterative relationship can be developed in which the models suggest more site locations, and the discovery of more sites, whether deliberate or by chance, is used to improve the model.

For the Mesolithic period in the Baltic, Fischer (1993, 1995) and Pedersen et al. (1997) have developed models for identifying the most probable locations of sites on submerged coastlines (where people would have established fishing sites) and their detection on the seabed by divers. This model has been developed and analyzed by Benjamin (2010). The model has been most effective under the circumstances provided by the low gradient, sediment-rich environment of the Baltic, but the general principles of attention to paleo-landscape and resource utilization can be extended and adapted to rocky coasts and other environments. The value of linking the dynamics of coastal changes during rising sea level to cultural patterns of hunting, fishing, and foraging has been further shown for the Baltic region by Jöns (2011) and by Lübke et al. (2011).

Since many coastal states have accepted the responsibility to manage and protect offshore prehistoric sites, heritage managers require a methodology for estimating the risk to seabed prehistory from different industry licensing regulations. Collaboration with industry can be very beneficial (e.g., Flemming, 2004a; Mol et al., 2008; Weerts et al., 2012; Moree and Sier, 2014), and over-restrictive controls result in chance finds not being reported. Models can therefore be used to classify regions so that appropriate relaxed or highly restrictive obligations can be placed on offshore operators seeking licenses (Flemming, 2004b; Faught and Flemming, 2008).



Submerged Continental Shelf Prehistory, Figure 8 The shoal banks northwest of Darwin, Australia, reveal a topography of planated karstic fossil reef limestone, with steep-sided valleys to 60–100 m, separating flat-topped banks at 30–36 m. At glacial sea-level lowstands, the valleys would have provided extremely sheltered marine environments with a wind fetch of 1–5 km, ideal for mangroves, mollusks, and possible human occupation (Map adapted from Veevers and Van Andel, 1967; see also Nutley, 2014).

Terrestrial taphonomy, site survival, site formation processes

The taphonomy of site abandonment, decay, burial, disturbance by animals or later cultural activities, and final formation of a stratified buried site on the exposed land of the continental shelf is the same as would occur on present land masses given the same climate conditions. Thus, while the factor is important, there is nothing unique about these stages which differentiates them from the usual considerations of site formation processes – up to the time that the site or landscape is inundated by the sea. The phrases "site formation" or "site formation processes" have considerable associated intellectual literature (e.g., Wood and Johnson, 1978; Stein, 2001), which will not be developed further here. Changes to the site deposit after abandonment may be cultural, such as a later period of occupation digging a pit or building a hearth, or noncultural due to soil processes, vegetation roots, diagenesis, rock falls, or landslides.

At this stage, we are concerned only with the mechanistic and sedimentary biogeochemical analysis of how sites survive, or do not, and we are not extending the interpretation to consider the way in which this biases the subsequent state of knowledge about the culture that created the sites. That bias manifestly occurs both before and after inundation and must be considered by future research. The large number of seabed sites that have been lost is probably not a random and unbiased sample of all the sites that have existed below present sea level.

Many submerged prehistoric sites that date from after the last glacial maximum (LGM) may have originated on, or very close to, the contemporaneous shoreline in tidal waters, such as the Bouldnor Cliff site, southern England (Momber, 2006; Momber et al., 2012). In these cases, the pre-inundation site formation may have occurred in wetlands, marshes, lagoons, or on dune ridges. The process of site survival in these conditions has been examined by Kraft et al. (1983), Belknap and Kraft (1981, 1985), and more recently by Boldurian (2006). Kelley et al. (2013) have analyzed site survival in the context of proven prehistoric remains in rocky terrain.

The processes of first marine transgression: transition of the surf zone, erosion or protection by topography, wind fetch, wave refraction, and lateral sediment transport

Masters and Flemming (1983) compiled data that reported several tens of submerged prehistoric sites globally, all in water shallower than 20 m, and each site protected naturally by some combination of lagoon, bay, limited wind fetch, estuary, low gradient beach, or rock protective barrier. In spite of the popular preconception that Bruun's Law (1962) necessarily results in unconsolidated coastal deposits being reworked, displaced, and redeposited downslope, these findings from many different countries have shown that prehistoric sites can and do survive for centuries and millennia in shallow marine environments and at constant sea level. The protecting factor, even during periods of prolonged sea-level stillstand, is local topography, wave climate, and currents. Cooper and Pilkey (2004) have presented a robust case for rejecting the generic application of Bruun's Law, and this would be consistent with the findings of many marine prehistoric sites.

The concatenation of circumstances that protect a site from the first wave attack during marine transgression includes a generally low gradient that dissipates offshore wave energy; restricted wind fetch (Figure 8), most effectively less than 5–10 km; a crenelated coastline of headlands; peat deposits; longshore transport moving sediment in front of the site; and bays, barriers, and islands that refract and diffract incoming waves or create complete wave shadows. Zhang et al. (2010) have constructed detailed three-dimensional analyses of the transgression process in the southern Baltic as it impacted upon the prehistoric coast of mostly unconsolidated sediments. The proposition that prehistoric sites are best protected by a rapid vertical rise of sea level has not been put to the test since the most rapid rates of rise were during the meltwater pulse around 15 ka BP, with a sea level 100 m lower than at present. The spatial density of Paleolithic sites would be low at that date, and the water depth is such that no systematic search has been conducted so far. Depending upon the previous dry-land processes of site formation, a particular site may be already protected or buried by accumulated sediment before marine transgression. Eighty percent of the sites with a recorded depth identified in the SPLASHCOS survey are shallower than 5 m, and some are intertidal, so it is clear that sites can survive in shallow water. Many were certainly destroyed as the sea rose to its present level, but some have survived.

Submerged Continental Shelf Prehistory, Figure 9 Three Acheulean hand axes found offshore in Table Bay, South Africa. They were embedded in red earth on bedrock beneath several meters of marine sands (Werz and Flemming, 2001; photo by Bruno Werz).

The effects of multiple marine transgressions and mechanisms by which prehistoric archaeological sites may survive several glacial cycles

Each glacial cycle tends to be a series of descending sawtooth stadials (Figure 4) during which the ice sheet expands, the sea level drops, and then there is a relatively abrupt partial melting phase. The next cold spell causes the ice sheet to expand even further, and the cycles repeat until, after about 100 ka years, the ice cap reaches a maximum extent, the sea level has dropped about 120–130 m, and then the ice melts over about 15–20 ka years. There are also shorter minor oscillations known as Dansgaard-Oeschger events. This typical sequence means that a prehistoric site dating from before the LGM may have been submerged and exposed several times, if it survives at all.

It has been shown that some sites can survive one inundation and survive hundreds of years in shallow water or deeper. Surviving multiple cycles implies that coastal erosion and redeposition on a large scale, combined with river sediment inputs, result in gradual sediment accumulation in a depocenter, so that prehistoric deposits are sealed in. As an example, the Quaternary multi-cycle paleotopographic evolution of the North Sea basin was extensively reviewed in a special journal issue (Cohen et al., 2014). In such buried conditions, prehistoric deposits are then only likely to be discovered by industrial activity or massive erosion. Thus, anthropogenic materials dating from 340 ka (Wessex Archaeology, 2011; Tizzard et al., 2014) were discovered in the sediments of the southern North Sea. Gaffney et al. (2007) interpret commercial geophysical seismic records to identify sub-bottom buried terrestrial landscape topography, including rivers, creeks, shorelines, marshes, and near-coast islands (Gaffney et al., 2007). Several sites with Neanderthal and Mesolithic skull fragments have been discovered in the southern North Sea (e.g., Hublin et al., 2009). Nevertheless, this generalization has exceptions, and the hand axes found by Bruno Werz in Table Bay, South Africa (Figure 9), have probably survived multiple glacial cycles while buried in several meters of sand and earth on an open exposed low gradient shore (Werz and Flemming, 2001), and an assemblage of flints off Cap Lévi, near Cherbourg, has

Submerged Continental Shelf Prehistory, Figure 10 Standard fish boxes landed at a Dutch port containing terrestrial Pleistocene bones and mammoth molars, obtained from one boat and 1 week of fishing. Tens of tons of Quaternary paleontological materials from the southern North Sea are landed each year (Photo by S. J. Kleinberg).

a date range of 50–100 ka BP, suggesting several periods of inundation and re-exposure (Cliquet et al., 2011). Another example of long-term survival of hominin remains on the continental shelf is the recovery by fishermen of an archaic hominin jawbone from a depth of 60–120 m in the Taiwan Straits, provisionally dated to later than 450 ka BP but likely in the range of 190–110 ka BP (Chang et al., 2015). Globally, there should be other identifiable depressions of the continental shelf that could preserve hominin/AMH deposits, though discovery of such anthropogenic traces is likely to depend on industrial activity and chance finds.

Modern sediment seabed conditions marine sediment movements, erosion, burial, processes of discovery of sites

Modern oceanographic and geomorphological processes are relevant to submerged prehistoric continental research and geoarchaeology for two reasons: (1) because the wind/wave/current forces and consequent sediment transport accretion/erosion determine whether the site is stable, will survive for a period of research, needs immediate rescue study, or should be excavated before it is destroyed and (2) because any operations conducted to examine the site are constrained by the oceanographic conditions, water depth, and distance from shore.

Most submerged prehistoric sites and paleontological finds on the continental shelf are discovered by chance (Figure 10). The exceptions are some sites in the Baltic and off the coast of Israel where the conditions are known so well that local marine archaeologists can monitor sand movements and winter storms and predict areas where they are likely to find new material. Continental shelf mapping programs are conducted by many countries for commercial reasons, but additional studies may be carried out specifically to identify potential preservation of prehistoric sites (e.g., TRC Environmental Corporation, 2012).

Site discovery is best promoted by seabed mapping programs that are sufficiently detailed to reveal submerged terrestrial features, combined with monitoring of chance finds by industrial operations, dredging, bottom trawling or scallop dredging, and good communications with recreational divers. Although sites have survived surprisingly often in shallow water, repeat observation of sites shows that erosion is occurring at some places, and this destroys known sites, while revealing fresh ones. The European project EMODNet (European Marine Observation and Data Network of the Directorate General of Maritime Affairs and Fisheries, European Commission) is extending its geological mapping data integration to include submerged Quaternary landscapes.

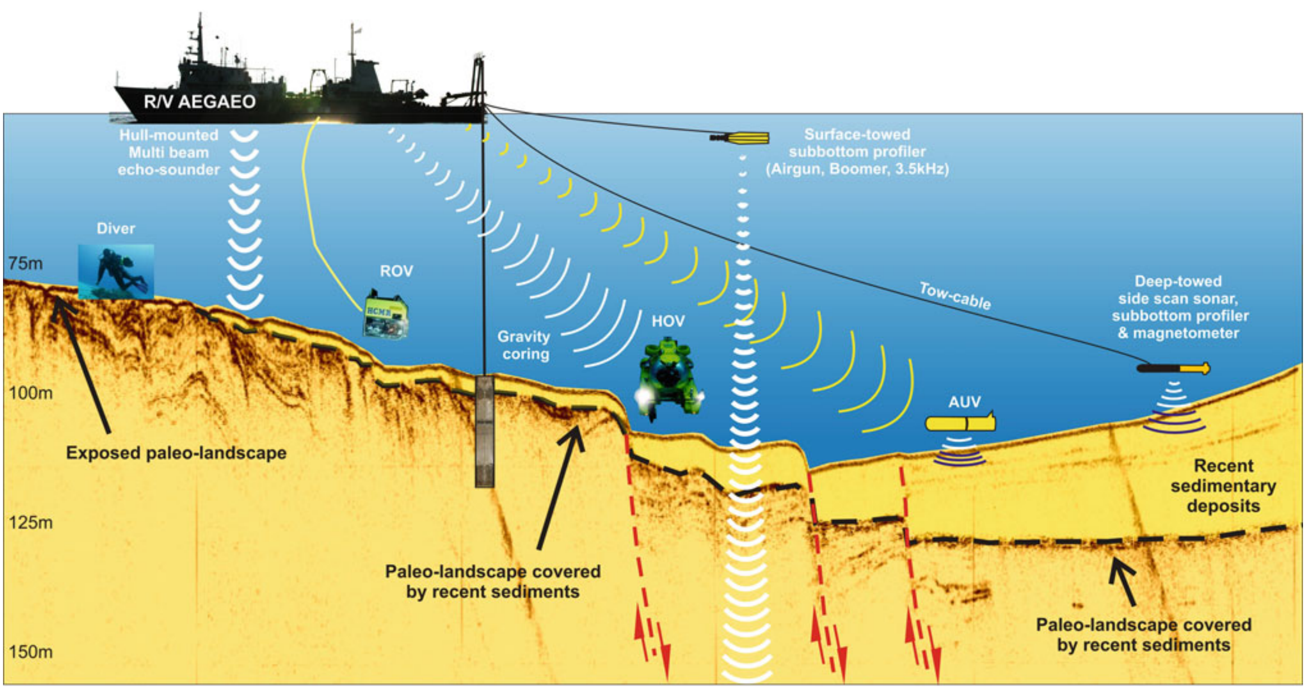
Application of modern oceanographic and commercial offshore technology to the search for, mapping of, and discovery of submerged prehistoric landscapes and archaeological sites

Discovery of seabed prehistoric sites usually occurs either through industry excavation or trawl nets recovering Pleistocene terrestrial bones (e.g., Chang et al., 2015) or through divers observing artifacts or bones or other anthropogenic signals. Detailed mapping, protection, and excavation have always so far required specially trained divers. Manuals written for marine archaeologists (e.g., Muckelroy, 1978; Green, 1990; Delgado, 1997; Ruppé and Barstad, 2002; Ballard, 2008; Bowens and NAS, 2008; Dellino-Musgrave, 2012) tend to devote almost all their attention to shipwreck archaeology, and thus practical guidance for research on prehistoric sites and landscapes is sparse, other than through the academic multi-author volumes already cited or examples from individual projects.

Both the search for high potential locations and the survey or excavation of individual sites can benefit from the utilization of acoustic equipment and techniques developed for the offshore industries (Figures 11 and 12). For detailed definitions of these methods, reference should be to the industrial and marine geoscience literature. A brief overview for submerged prehistoric research is provided in a chapter by Tine Missiaen and Dimitris Sakellariou in the European Marine Board report (Flemming et al., 2014, 95–115).

The logical necessity of linking prehistoric sites to the contemporary landscape and environmental resources has encouraged the publication of several studies of regional submerged landscapes and their evolution through time (e.g., Gaffney et al., 2007; Cohen et al., 2014) in the North Sea, while other projects have focused on building up a geomorphological picture of the regional submerged landscape as a stage in searching for sites in the Red Sea (e.g., Bailey et al., 2015). Such studies mean that

Submerged Continental Shelf Prehistory, Figure 11 In order to map the submerged Bronze Age town of Pavlopetri, Greece, an autonomous underwater vehicle (AUV) was equipped with a GPS navigation system and digitized stereoscopic photogrammetry (see Henderson et al., 2011, 2013; photo by Jon Henderson, with permission).



Submerged Continental Shelf Prehistory, Figure 12 Diagram of acoustic systems and other techniques applicable to prehistoric continental shelf research. Graphic by the Hellenic Centre for Marine Research and courtesy of Dimitris Sakellariou.

as soon as a site is discovered or if sites are already known, they can then be fitted into the landscape, and archaeologists can start to interpret the region from a cultural and paleo-technological perspective.

Wessex Archaeology (2011) and Tizzard et al. (2014) provide an example of commercial offshore technology techniques adapted to the testing and sampling of an important Middle Paleolithic site at a depth of 16–35 m in the North Sea. Grøn and Boldreel (2014) show how acoustic chirp technology can be used to reveal buried materials such as wood in a way that could detect prehistoric timbers such as hut foundations.

Survey, conservation, monitoring, excavation, and management of seabed prehistoric sites in the context of the UNESCO convention on protection of the underwater cultural heritage

Seabed prehistoric sites can and do survive, but erosion of sites is sometimes observed in unconsolidated sediments at all depths both from wave action and tidal currents. Many sites have been lost already. Thus, observation, reporting, surface surveying, and continuous multi-year monitoring are advisable where possible. The UNESCO Convention on the Protection of the Underwater Cultural Heritage applies to submerged prehistoric sites (Flemming et al., 2014, 34; Salter et al., 2014, 155), and coastal states signatories to the Convention have obligations toward protecting sites within their jurisdiction.

Coastal states have conducted assessment surveys (e.g., TRC Environmental Corporation, 2012) identifying terrains which indicate (1) the probability of site occupation and (2) the probability of site survival. As discussed above, these do not amount to accurate site prediction models. Where known sites are fragile or vulnerable to erosion, mapping and sampling can provide data before the material is destroyed. The decision to excavate a site may be taken because of incipient disturbance by industrial development (e.g., Moree and Sier, 2014) or because of continuous erosion (Momber et al., 2012). Experience in many countries is now sufficient to justify excavation to the highest standards of accuracy, recording, and laboratory study of materials (e.g., Galili et al., 2004; Cliquet et al., 2011; Henderson et al., 2011; Andersen, 2013; Carabias Amor et al., 2014) (Figure 13). State heritage agencies in many countries now recognize the importance of continental shelf prehistoric research, and the offshore mapping programs that are primarily funded to support offshore industry, safe navigation, or military purposes can be planned with minimal extra cost to include the components and methods of interpretation that enable reconstruction of past terrestrial landscapes.

Value of discoveries so far: the link between seabed mapping and site detection

Given the persistent skepticism about the possibility of conducting archaeological research on seabed prehistoric sites, one of the main achievements of the last 50 years has been to establish beyond doubt that sites do exist, that they can survive sometimes with intact stratification, that they exist off almost all continents, and that they can preserve organic materials and date to all archaeological periods of the last million years.

Because of the slow rate of discovery in most areas, known sites are scattered randomly and widely in space and time so that it is difficult to apply modern methodology to more than one site at a time. The obvious cure for this problem is to find more sites, but there is still no reliable means using remote sensing to find them. We are limited to the natural to-and-fro collaboration between industry, fishermen, dredgers, amateurs, paleontologist collectors, and the professional academics and cultural heritage agencies to exchange information.

Submerged Continental Shelf Prehistory, Figure 13 Diver at the submerged Bronze Age town of Pavlopetri, Greece, working over a rigid steel survey grid and excavating a large ceramic vessel using a pump dredge (Photo by Jon Henderson, with permission).

Mapped and excavated submerged sites have revealed an extraordinary richness of preserved organics, including human and animal bones, antlers, burials, hearths with charcoal and burnt food, nuts, seeds, leaves, string, leather, clothing, canoes, and paddles. In places where primary stratified deposits can be excavated, as in the Baltic or off the Mediterranean coast of Israel, deposits show Mesolithic multi-family settlements, with a complex structure.

In the southern Baltic and on the Mediterranean coast of Israel (Figure 14), numerous sites in the age range of 5,000–10,000 years BP have been found in proximity so that it has been possible to reconstruct population patterns, seasonal changes in food sources (Fischer, 2002), freshwater supply, fishing methods, population age structure, causes of mortality, and so on. A steady increase in the temporal-spatial density of known sites in the North Sea, based on a growing understanding of the geomorphological and oceanographic changes over the last million years (Cohen et al., 2014), is beginning to create a similar situation at least as a future goal. In contrast, finds on the seaboard of the USA are still sparse but gradually building up a picture of remains enduring over a long time span since the earliest occupation of the Americas (Faught and Gusick, 2011; Stanford et al., 2014).

Submerged Continental Shelf Prehistory, Figure 14 Atlit, Israel, diver lifting finds from a submerged freshwater well on the seafloor (Photo by I. Greenberg and courtesy of E. Galili, Israel Antiquities Authority and Haifa University).

New frontiers

As of 2015, there remain several technical and geographical challenges that need to be confronted, in addition to improving the detailed geoarchaeological interpretation of known sites and integrating data from the shelf with the hinterland.

These are

1. Gathering more data from the deeper shelf, out to 100–120 m depth, coinciding in most areas with the shoreline of the LGM. Paleolithic site density will be very low, but it could be important to correlate such sites with the population displacement caused by the maximum extent of the ice sheets in Eurasia and the possible earliest movements into North America from Siberia.
2. So far, no multi-layer stratified anthropogenic deposits have been found in submerged sea caves, although many thousands of caves have been mapped by speleologists and enthusiast cave divers. The reasons for this need thorough examination with possible development of a new strategy to discover occupied caves or prove their absence.
3. Shell middens have not been found underwater off coasts where thousands of middens exist above sea level on the modern coast. Some anthropogenic shell deposits have been found associated with muddy or marsh deposits in the Baltic, but in general, they have not been found offshore. This needs checking to see whether all middens are necessarily destroyed by inundation or whether some could have survived, leaving identifiable scattered deposits.
4. There is no remote sensing acoustic or electrical system that can detect prehistoric archaeological deposits on the seafloor. Optical photo-video systems can identify lithics and bones provided they are on the surface, but the visibility range is very restricted and sometimes zero. Logically, geochemical or genetic/DNA detection might be able to define gradients in the proximity of an anthropogenic site that could lead to identification of the center, where artifacts are most likely to be found.
5. The lack of known seabed prehistoric sites in the tropics is an anomaly. A fresh approach to the environmental conditions and landscapes of the exposed shelf in the tropics is needed, followed by searching for anthropogenic signals.
6. Artifacts and sites are already known that predate the LGM, and some have survived two or more glacial cycles. While discovery is most likely to be through industrial excavation or dredging, every effort should be made to respond quickly to chance finds.
7. Humans were living on islands off the Arctic coast of Russia before the LGM. Further work is needed to understand the communities that lived in the polar region before and immediately after the LGM.

Conclusions

The prehistoric geoarchaeology of the continental shelf is a highly complex, multidisciplinary topic that has grown slowly but steadily during the last 50 years. Thousands of seabed prehistoric sites have been discovered and studied by researchers, while improvements in marine technology mean that seabed mapping, landscape interpretation, and site survey, protection, and excavation can be carried out with increased efficiency and reduced cost. Continued progress will provide fundamental data to help understand crucial stages of human evolution, the development of technical skills, and the migration and dispersal of groups throughout the globe.

Bibliography

Allen, J., Golson, J., and Jones, R. (eds.), 1977. *Sunda and Sahul: Prehistoric Studies in Southeast Asia, Melanesia and Australia*. London: Academic.

Andersen, S. H., 1980. Tybrind Vig. Foreløbig meddelelse om en undersøisk stenalderboplads ved Lillebælt [Tybrind Vig. A preliminary report on a submerged Ertebølle settlement on the Little Belt]. *Antikvariske Studies*, **4**, 7–22 (in Danish).

Andersen, S. H., 1985. Tybrind Vig. A preliminary report on a submerged Ertebølle settlement on the west coast of Fyn. *Journal of Danish Archaeology*, **4**(1), 52–69.

Andersen, S. H. (ed.), 2013. *Tybrind Vig: Submerged Mesolithic Settlements in Denmark*. Hojbjerg: Moesgård Museum, Jutland Archaeological Society, and Aarhus: Aarhus University Press.

Anderson, A., Barrett, J. H., and Boyle, K. V. (eds.), 2010. *The Global Origins and Development of Seafaring*. Cambridge: McDonald Institute for Archaeological Research.

Bailey, G. N., and Flemming, N. C., 2008. Archaeology of the continental shelf: marine resources, submerged landscapes and underwater archaeology. *Quaternary Science Reviews*, **27** (23–24), 2153–2165.

Bailey, G. N., and King, G. C. P., 2011. Dynamic landscapes and human dispersal patterns: tectonics, coastlines, and the reconstruction of human habitats. *Quaternary Science Reviews*, **30** (11–12), 1533–1553.

Bailey, G., Devès, M., Inglis, R. H., Meredith-Williams, M. G., Momber, G. L., Sinclair, A., Sakellariou, D., Rousakis, G., Al Ghamdi, S., and Alsharekh, A., 2015. Blue Arabia: palaeolithic and underwater survey in SW Saudi Arabia and the role of coasts in Pleistocene dispersal. *Quaternary International*, doi:10.1016/j.quaint.2015.01.002.

Ballard, R. D. (ed.), 2008. *Archaeological Oceanography*. Princeton: Princeton University Press.

Bednarik, R. G., 2003. Seafaring in the Pleistocene. *Cambridge Archaeological Journal*, **13**(1), 41–66.

Belknap, D. F., and Kraft, J. C., 1981. Preservation potential of transgressive coastal lithosomes on the U.S. Atlantic shelf. *Marine Geology*, **42**(1–4), 429–442.

Belknap, D. F., and Kraft, J. C., 1985. Influence of antecedent geology on stratigraphic preservation potential and evolution of Delaware's barrier systems. *Marine Geology*, **63**(1–4), 235–262.

Benjamin, J., 2010. Submerged prehistoric landscapes and underwater site discovery: reevaluating the 'Danish Model' for international practice. *Journal of Island and Coastal Archaeology*, **5**(2), 253–270.

Benjamin, J., Bonsall, C., Pickard, C., and Fischer, A. (eds.), 2011. *Submerged Prehistory*. Oxford: Oxbow.

Blanc, A. C., 1940. *Industrie musteriane e paleolitiche superiori nelle dune fossile e nelle grotte litorannee del Capo Palinuro*. Roma: G. Bardi. Rendiconti della Classe di Scienze fisiche, matematiche e naturali, della Reale Accademia d'Italia, Ser.VII, Vol. 1.

Boldurian, A. T., 2006. Clovis fluted point from coastal waters in southern New Jersey. *North American Archaeologist*, **27**(3), 245–270.

Boule, M., 1906. Géologie et paléontologie. In de Villeneuve, L., Boule, M., Verneau, R., and Cartailhac, E. (eds.), *Les Grottes de Grimaldi*. Monaco: Imprimerie de Monaco, Vol. 1, pp. 73–156. Fasc. 2.

Bowens, A., and NAS (Nautical Archaeological Society), 2008. *Archaeology Underwater. NAS Guide to Principles and Practice*, 2nd edn. Oxford: Wiley/Blackwell.

Bruun, P., 1962. Sea-level rise as a cause of shore erosion. *Journal of Waterways and Harbors Division (American Society of Civil Engineers)*, **88**(1), 117–132.

Bulbeck, D., 2007. Where river meets sea: a parsimonious model for *Homo sapiens* colonization if the Indian Ocean Rim and Sahul. *Current Anthropology*, **48**(2), 315–321.

Burkitt, M. C., 1932. A Maglemose harpoon dredged up recently from the North Sea. *Man*, **32**, 118.

Buynevich, I. V., Yanko-Hombach, V., Gilbert, A. S., and Martin, R. E. (eds.), 2011. *Geology and Geoarchaeology of the Black Sea Region: Beyond the Flood Hypothesis*. Boulder: Geological Society of America. GSA Special Paper 473.

Carabias Amor, D., Cartajena, I., Simonetti, R., López, P., Morales, C., and Ortega, C., 2014. Submerged paleolandscapes: site GNL Quintero 1 (GNLQ1) and the first evidence from the Pacific coast of South America. In Evans, A. M., Flatman, J. C., and Flemming, N. C. (eds.), *Prehistoric Archaeology on the Continental Shelf: A Global Review*. New York: Springer, pp. 131–150.

Carrión, J. S., Finlayson, C., Fernández, S., Finlayson, G., Allué, E., López-Sáez, J. A., López-García, P., Gil-Romera, G., Bailey, G., and González-Sampériz, P., 2008. A coastal reservoir of biodiversity for upper Pleistocene human populations: palaeoecological investigations in Gorham's Cave (Gibraltar) in the context of the Iberian Peninsula. *Quaternary Science Reviews*, **27**(23–24), 2118–2135.

Carter, R. W. G., 1993. *Coastal Environments: An Introduction to the Physical, Ecological and Cultural Systems of Coastlines*. London: Academic Press.

Chang, C.-H., Kaifu, Y., Takai, M., Kono, R. T., Grün, R., Matsu'ura, S., Kinsley, L., and Lin, L.-K., 2015. The first archaic *Homo* from Taiwan. *Nature Communications*, **6**, 6037, doi:10.1038/ncomms7037.

Chiocci, F. L., and Chivas, A. R. (eds.), 2014. *Continental Shelves of the World: Their Evolution During the Last Glacio-Eustatic Cycle*. London: The Geological Society. Geological Society, London, Memoir 41.

Clausen, C. J., Cohen, A. D., Emiliani, C., Holman, J. A., and Stipp, J. J., 1979. Little salt spring, Florida: a unique underwater site. *Science*, **203**(4381), 609–614.

Cliquet, D., Coutard, S., Clet, M., Allix, J., Tessier, B., Lelong, F., Baltzer, A., Mear, Y., Poizot, E., Auguste, P., Alix, P., Olive, J., and Guesnon, J., 2011. The middle palaeolithic underwater site of La Mondrée, Normandy, France. In Benjamin, J., Bonsall, C., Pickard, C., and Fischer, A. (eds.), *Submerged Prehistory*. Oxford: Oxbow Books, pp. 111–128.

Clottes, J., and Courtin, J., 1996. *The Cave Beneath the Sea: Paleolithic Images at Cosquer*. New York: Harry N. Abrams.

Clottes, J., Courtin, J., and Vanrell, L., 2005. *Cosquer redécouvert*. Paris: Seuil.

Cockerell, W. A., and Murphy, L., 1978. Inundated terrestrial sites: 8 SL 17: methodological approaches to a dual component marine site on the Florida Atlantic coast. In Barto Arnold, J., III (ed.), *Beneath the Waters of Time: Proceedings of the 9th Conference on Underwater Archaeology*. Austin: Texas Antiquities Committee. Texas Antiquities Committee Publication 6, pp. 175–182.

Cohen, K. M., Gibbard, P. L., and Weerts, H. J. T., 2014. North Sea palaeogeographical reconstructions for the last 1 Ma. *Netherlands Journal of Geosciences*, **93**(1–2), 7–29.

Collina-Girard, J., 2005. La Grotte Cosquer, témoin émergé d'un monde englouti. In Clottes, J., Courtin, J., and Vanrell, L. (eds.), *Cosquer redécouvert*. Paris: Seuil, pp. 52–55.

Cooper, J. A. G., and Pilkey, O. H., 2004. Sea-level rise and shoreline retreat: time to abandon the Bruun rule. *Global and Planetary Change*, **43**(3–4), 157–171.

Crock, J. G., Petersen, J. B., and Andersen, R. M., 1993. Scalloping for artifacts: a biface and plummet from eastern Blue Hill Bay, Maine. *Archaeology of Eastern North America*, **21**, 179–192.

Davidson-Arnott, R., 2010. *Introduction to Coastal Processes and Geomorphology*. Cambridge: Cambridge University Press.

Delgado, J. P., 1997. *Encyclopedia of Underwater and Maritime Archaeology*. London: Yale University Press.

Dellino-Musgrave, V. E., 2012. *Marine Archaeology: A Handbook*. Bootham: Council for British Archaeology.

Dixon, J. E., and Monteleone, K., 2014. Gateway to the Americas: underwater archaeological survey in Beringia and the North Pacific. In Evans, A. M., Flatman, J. C., and Flemming, N. C. (eds.), *Prehistoric Archaeology on the Continental Shelf: A Global Review*. New York: Springer, pp. 95–114.

Emery, K. O., and Edwards, R. L., 1966. Archaeological potential of the Atlantic continental shelf. *American Antiquity*, **31**(5), 733–737.

Erlandson, J. M., and Braje, T. J., 2015. Coasting out of Africa: the potential of mangrove forests and marine habitats to facilitate human coastal expansion via the southern dispersal route. *Quaternary International*, doi:10.1016/j.quaint.2015.03.046.

Erlandson, J. M., Braje, T. J., Gill, K. M., and Graham, M. H., 2015. Ecology of the Kelp Highway: did marine resources facilitate human dispersal from Northeast Asia to the Americas? *Journal of Island and Coastal Archaeology*, doi:10.1080/15564894.2014.1001923.

Evans, A. M., Flatman, J. C., and Flemming, N. C. (eds.), 2014. *Prehistoric Archaeology on the Continental Shelf: A Global Review*. New York: Springer.

Faught, M. K., 2004. The underwater archaeology of paleolandscapes, Apalachee Bay, Florida. *American Antiquity*, **69**(2), 275–289.

Faught, M. K., 2014. Remote sensing, target identification and testing for submerged prehistoric sites in Florida: process and protocol in underwater CRM projects. In Evans, A. M., Flatman, J. C., and Flemming, N. C. (eds.), *Prehistoric Archaeology on the Continental Shelf: A Global Review*. New York: Springer, pp. 37–52.

Faught, M. K., and Flemming, N. C., 2008. Submerged prehistoric sites: 'Needles in haystacks' for CRMs and industry. *Sea Technology*, **49**(10), 37–38. 40–42.

Faught, M. K., and Gusick, A. E., 2011. Submerged prehistory in the Americas. In Benjamin, J., Bonsall, C., Pickard, C., and Fischer, A. (eds.), *Submerged Prehistory*. Oxford: Oxbow Books, pp. 145–157.

Faure, H., Walter, R. C., and Grant, D. R., 2002. The coastal oasis: ice age springs on emerged continental shelves. *Global and Planetary Change*, **33**(1–2), 47–56.

Fedje, D. W., and Josenhans, H., 2000. Drowned forests and archaeology on the continental shelf of British Columbia, Canada. *Geology*, **28**(2), 99–102.

Fischer, A., 1993. *Stenalderbopladser på bunden af Smålandsfarvandet: En teori afprøvet ved dykkerbesigtigelse [Stone Age Settlements in the Småland Bight: A Theory Tested by Diving]*. København: Miljøministeriet Skov- og Naturstyrelsen.

Fischer, A. (ed.), 1995. *Man and Sea in the Mesolithic: Coastal Settlement Above and Below Present Sea Level. Proceedings of the International Symposium, Kalundborg, Denmark 1993*. Oxford: Oxbow Books. Oxbow Monographs 53.

Fischer, A., 2002. Food for feasting? An evaluation of explanations of the neolithisation of Denmark and southern Sweden. In Fischer, A., and Kristiansen, K. (eds.), *The Neolithisation of Denmark—150 years of Debate*. Sheffield: J.R. Collis. Sheffield Archaeological Monographs 12, pp. 343–393.

Fladmark, K. R., 1975. *Paleoecological Model for Northwest Coast Prehistory*. Ottawa: Archaeological Survey of Canada. National Museum of Man Mercury Series. Archaeological Survey of Canada Paper 43.

Flemming, N. C., 1968. Derivation of Pleistocene marine chronology from the morphometry of erosion profiles. *Journal of Geology*, **76**(3), 280–296.

Flemming, N. C. (ed.), 2004a. *Submarine Prehistoric Archaeology of the North Sea: Research Priorities and Collaboration with Industry*. York: Council for British Archaeology. Research Report 141.

Flemming, N. C., 2004b. The scope of strategic environmental assessment of North Sea area SEA5 in regard to prehistoric archaeological remains. Department of Trade and Industry, Consultation Document, Technical Report. http://www.offshore-sea.org.uk/consultations/SEA_5/SEA5_TR_Archaeology_NCF.pdf.

Flemming, N. C., Bailey, G. N., and Sakellariou, D., 2012. Migration: value of submerged early human sites. *Nature*, **486**(7401), 34.

Flemming, N. C., Çağatay, M. N., Chiocci, F. L., Galanidou, N., Jöns, H., Lericolais, G., Missiaen, T., Moore, F., Rosentau, A., Sakellariou, D., Skar, B., Stevenson, A., and Weerts, H., 2014. *Land Beneath the Waves: Submerged Landscapes and Sea Level Change. A Joint Geoscience-Humanities Strategy for European Continental Shelf Prehistoric Research*. Ostend: European Marine Board. European Marine Board Position Paper 21.

Forster, P., 2004. Ice ages and the mitochondrial DNA chronology of human dispersals: a review. *Philosophical Transactions of the Royal Society of London B*, **358**(1442), 255–264.

Fu, Q., Li, H., Moorjani, P., Jay, F., Slepchenko, S. M., Bondarev, A. A., Johnson, P. L., Aximu-Petri, A., Prüfer, K., de Filippo, C., Meyer, M., Zwyns, N., Salazar-García, D. C., Kuzmin, Y. V., Keates, S. G., Kosintsev, P. A., Razhev, D. I., Richards, M. P., Peristov, N. V., Lachmann, M., Douka, K., Higham, T. F., Slatkin, M., Hublin, J. J., Reich, D., Kelso, J., Viola, T. B., and Pääbo, S., 2014. Genome sequence of a 45,000-year-old modern human from western Siberia. *Nature*, **514**(7523), 445–449.

Gaffney, V. L., Thomson, K., and Fitch, S. (eds.), 2007. *Mapping Doggerland: The Mesolithic Landscapes of the Southern North Sea*. Oxford: Archaeopress.

Gagliano, S. M., Pearson, C. E., Weinstein, R. A., Wiseman, D. E., and McClendon, C. M., 1982. *Sedimentary Studies of Prehistoric Archaeological Sites: Criteria for the Identification of Submerged Archaeological Sites of the Northern Gulf of Mexico Continental Shelf*. Baton Rouge: Coastal Environments.

Galili, E., Weinstein-Evron, M., Hershkovitz, I., Gopher, A., Kislev, M., Lernau, O., Kolska-Horwitz, L., and Lernau, H., 1993. Atlit-Yam: a prehistoric site on the sea floor off the Israeli coast. *Journal of Field Archaeology*, **20**(2), 133–157.

Galili, E., Lernau, O., and Zohar, I., 2004. Fishing and coastal adaptations at 'Atlit-Yam—a submerged PPNC fishing village off the Carmel coast, Israel. *Atiqot*, **48**, 1–34.

Green, J. N., 1990. *Maritime Archaeology: A Technical Handbook*. London: Academic Press Inc.

Grøn, O., and Boldreel, L. O., 2014. Chirping for large-scale maritime archaeological survey: a strategy developed from a practical experience-based approach. *Journal of Archaeology*, 2014: Article ID 147390. http://dx.doi.org/10.1155/2014/147390.

Harding, A. F., Cadogan, G., and Howell, R., 1969. Pavlopetri, an underwater Bronze Age town in Laconia. *Annual of the British School at Athens*, **64**, 113–142.

Harff, J., and Lüth, F. (eds.), 2011. *SINCOS II. Sinking Coasts: Geosphere, Ecosphere and Anthroposphere of the Holocene Southern Baltic Sea*. Mainz: Verlag Philipp von Zabern. Bericht der Romisch-Germanischen Kommission 92.

Harff, J., Lemke, W., Lampe, R., Lüth, F., Lübke, H., Meyer, M., Tauber, F., and Schmölcke, U., 2007a. The Baltic Sea coast—a model of interrelations among geosphere, climate, and anthroposphere. In Harff, J., Hay, W. W., and Tetzlaff, D. M. (eds.), *Coastline Changes: Interrelation of Climate and Geological Processes*. Boulder: Geological Society of America. GSA, Special Paper 426, pp. 133–142.

Harff, J., Hay, W. W., and Tetzlaff, D. M. (eds.), 2007b. *Coastline Changes: Interrelation of Climate and Geological Processes*. Boulder: Geological Society of America. GSA Special Paper 426.

Harff, J., Bailey, G., and Lüth, F. (eds.), 2015. *Geology and Archaeology: Submerged Landscapes of the Continental Shelf*. Geological Society, London, Special Publications, 411, http://doi.org/10.1144/SP411.10.

Hayashida, K., 1993. *The Archaeological Materials from the Takashima Seabed* (*Part II*). Takashima Town Cultural Property Research Report. Educational Committee of Takashima Town, Nagasaki Prefecture. (in Japanese, with short English summary).
Henderson, J. C., Gallou, C., Flemming, N. C., and Spondylis, E., 2011. The Pavlopetri underwater archaeology project: investigating an ancient submerged town. In Benjamin, J., Bonsall, C., Pickard, C., and Fischer, A. (eds.), *Submerged Prehistory*. Oxford: Oxbow Books, pp. 207–218.
Henderson, J., Pizarro, O., Johnson-Roberson, M., and Mahon, I., 2013. Mapping submerged archaeological sites using stereo-vision photogrammetry. *International Journal of Nautical Archaeology*, **42**(2), 243–256.
Henn, B. M., Cavalli-Sforza, L. L., and Feldman, M. W., 2012. The great human expansion. *Proceedings of the National Academy of Sciences*, **109**(44), 17758–17764.
Hill, C., Soares, P., Mormina, M., Macaulay, V., Clarke, D., Blumbach, P. B., Vizuete-Forster, M., Forster, P., Bulbeck, D., Oppenheimer, S., and Richards, M., 2007. A mitochondrial stratigraphy for island southeast Asia. *American Journal of Human Genetics*, **80**(1), 29–43.
Hublin, J.-J., Weston, D., Gunz, P., Richards, M., Roebroeks, W., Glimmerveen, J., and Anthonis, L., 2009. Out of the North Sea: the Zeeland ridges Neandertal. *Journal of Human Evolution*, **57**(6), 777–785.
Jöns, H., 2011. Settlement development in the shadow of coastal changes—case studies from the Baltic rim. In Harff, J., Björck, S., and Hoth, P. (eds.), *The Baltic Sea Basin*. Heidelberg: Springer, pp. 301–336.
Jöns, H., Mennenga, M., Schaap, D., 2016. On behalf of the Splashcos-network. The SPLASHCOS Viewer: a European information system about submerged prehistoric sites on the continental shelf. http://splashcos.maris2.nl.
Joordens, J. C. A., d'Errico, F., Wesselingh, F. P., Munro, S., de Vos, J., Wallinga, J., Ankjærgaard, C., Reimann, T., Wijbrans, J. R., Kuiper, K. F., Mücher, H. J., Coqueugniot, H., Prié, V., Joosten, I., van Os, B., Schulp, A. S., Panuel, M., van der Haas, V., Lustenhouwer, W., Reijmer, J. J. G., and Roebroeks, W., 2015. *Homo erectus* at Trinil on Java used shells for tool production and engraving. *Nature*, **518**(7538), 228–231.
Josenhans, H., Fedje, D., Pienitz, R., and Southon, J., 1997. Early humans and rapidly changing Holocene sea levels in the Queen Charlotte Islands-Hecate Strait, British Columbia, Canada. *Science*, **277**(5322), 71–74.
Kelley, J. T., Belknap, D. F., Kelley, A. R., and Claesson, S. H., 2013. A model for drowned terrestrial habitats with associated archeological remains in the northwestern Gulf of Maine, USA. *Marine Geology*, **338**, 1–16.
King, G., and Bailey, G. N., 2006. Tectonics and human evolution. *Antiquity*, **80**(308), 265–286.
Klein, R. G., 2009. *The Human Career*, 3rd edn. Chicago: University of Chicago Press.
Kraft, J. C., Belknap, D. F., and Kayan, I., 1983. Potentials of discovery of human occupation sites on the continental shelf and near shore coastal zone. In Masters, P. M., and Flemming, N. C. (eds.), *Quaternary Coastlines and Marine Archaeology: Towards the Prehistory of Land Bridges and Continental Shelves*. London: Academic Press, pp. 87–120.
Kuhn, S. L., Stiner, M. C., Güleç, E., Özer, I., Yılmaz, H., Baykara, I., Açıkkol, A., Goldberg, P., Martínez Molina, K., Ünay, E., and Suata-Alpaslan, F., 2009. The early upper Paleolithic occupations at Uçağızlı cave (Hatay, Turkey). *Journal of Human Evolution*, **56**(2), 87–113.
Lambeck, K., and Purcell, A., 2005. Sea-level change in the Mediterranean Sea since the LGM: model predictions for tectonically stable areas. *Quaternary Science Reviews*, **24**(18–19), 1969–1988.
Lambeck, K., Rouby, H., Purcell, A., Sun, Y., and Sambridge, M., 2014. Sea level and global ice volumes from the Last Glacial Maximum to the Holocene. *Proceedings of the National Academy of Sciences*, **111**(43), 15296–15303.
Long, D., Wickham-Jones, C. R., and Ruckley, N. A., 1986. A flint artefact from the northern North Sea. In Roe, D. A. (ed.), *Studies in the Upper Palaeolithic of Britain and NorthWest Europe*. Oxford: British Archaeological Reports. British Archaeological Reports, International Series 296, pp. 55–62.
Louwe Kooijmans, L. P., 1970–71. Mesolithic bone and antler implements from the North Sea and from the Netherlands. *Berichten van de Rijksdienst voor het Oudheidkundig Bodemonderzoek*, 20–21: 27–73.
Lübke, H., Schmölcke, U., and Tauber, F., 2011. Mesolithic hunter-fishers in a changing world: a case study of submerged sites on the Jäckelberg, Wismar Bay, northeastern Germany. In Benjamin, J., Bonsall, C., Pickard, C., and Fischer, A. (eds.), *Submerged Prehistory*. Oxford: Oxbow Books, pp. 21–37.
Marino, G., Rohling, E. J., Rodriguez-Sanz, L., Grant, K. M., Heslop, D., Roberts, A. P., Stanford, J. D., and Yu, J., 2015. Bipolar seesaw control on last interglacial sea level. *Nature*, **522**(7555), 197–201.
Masters, P. M., and Flemming, N. C. (eds.), 1983. *Quaternary Coastlines and Marine Archaeology: Towards the Prehistory of Land Bridges and Continental Shelves*. London: Academic Press.
Micallef, A., Foglini, F., Le Bas, T., Angeletti, L., Maselli, V., Pasuto, A., and Taviani, M., 2013. The submerged paleolandscape of the Maltese Islands: morphology, evolution and relation to quaternary environmental change. *Marine Geology*, **335**, 129–147.
Mol, D., de Vos, J., Bakker, R., van Giel, B., Glimmerveen, J., van der Plicht, H., and Post, K., 2008. *Kleine encyclopedie van het leven in het Pleistoceen: Mammoeten, neushoorns en andere dieren van de Noordzeeboden*. Diemen: Veen Magazines. De wetenschappelijke bibliotheek van natuurwetenschap en techniek 94 (in Dutch).
Momber, G., 2006. Mesolithic occupation: 11 m below the waves. In Hafner, A., Niffler, U., and Ruoff, U. (eds.), *Die neue Sicht: Unterwasserarchäologie und Geschichtsbild; Akten des 2. Internationalen Kongresses für Unterwasserarchäologie, Rüschlikon bei Zürich, 21.–24. Oktober 2004 [The New View: Underwater Archaeology and the Historic Picture]*. Basel: Archäologie Schweiz. Antiqua 40, pp. 56–63.
Momber, G. L., Bailey, G., and Moran, L., 2012. Identifying the archaeological potential of submerged landscapes. In Henderson, J. (ed.), *Beyond Boundaries: Proceedings of the 3rd International Congress on Underwater Archaeology, 9th to the 12th July, 2008, London*. Bonn: Habelt, pp. 257–268.
Moree, J. M., and Sier, M. M. (eds.), 2014. *Twintig meter diep! Mesolithicum in de Yangtzehaven-Massvlakte te Rotterdam: Landschapsontwikkeling en bewoning in het Vroeg Holoceen*. Rotterdam: Bureau Oudheidkundig Onderzoek Rotterdam, With digital annexes. BOORapporten 523. in Dutch.
Muckelroy, K., 1978. *Maritime Archaeology*. Cambridge: Cambridge University Press.
North, F. J., 1957. *Sunken Cities: Some Legends of the Coast and Lakes of Wales*. Cardiff: University of Wales Press.
Nutley, D., 2014. Inundated site studies in Australia. In Evans, A. M., Flatman, J. C., and Flemming, N. C. (eds.), *Prehistoric Archaeology on the Continental Shelf: A Global Review*. New York: Springer, pp. 255–273.
Pedersen, L. D., Fischer, A., and Aaby, B., 1997. *The Danish Storebælt since the Ice Age: Man, Sea and Forest*. Copenhagen:

A/S Storebælt Fixed Link in co-operation with Kalundborg Regional Museum, the National Forest and Nature Agency, and the National Museum of Denmark. Storebælt Publications.

Peltier, W. R., and Fairbanks, R. G., 2006. Global glacial ice volume and Last Glacial Maximum duration from an extended Barbados sea level record. *Quaternary Science Reviews*, **25**(23–24), 3322–3337.

Pope, K. O., and Terrell, J. E., 2008. Environmental setting of human migrations in the circum-Pacific region. *Journal of Biogeography*, **35**(1), 1–21.

Reid, C., 1913. *Submerged Forests*. Cambridge: Cambridge University Press.

Rodríguez-Vidal, J., d'Errico, F., Giles Pacheco, F., Blasco, R., Rosell, J., Jennings, R. P., Queffelec, A., Finlayson, G., Fa, D. A., Gutiérrez López, J. M., Carrión, J. S., Negro, J. S., Finlayson, S., Cáceres, L. M., Bernal, M. A., Fernández Jiménez, S., and Finlayson, C., 2014. A rock engraving made by Neanderthals in Gibraltar. *Proceedings of the National Academy of Sciences*, **111**(37), 13301–13306.

Rohling, E. J., Grant, K., Bolshaw, M., Roberts, A. P., Siddall, M., Hemleben, C., and Kucera, M., 2009. Antarctic temperature and global sea level closely coupled over the past five glacial cycles. *Nature Geoscience*, **2**, 500–504.

Ruppé, R. J., 1978. Underwater site detection by use of a coring instrument. In Barto Arnold, J., III (ed.), *Beneath the Waters of Time: Proceedings of the 9th Conference on Underwater Archaeology*. Austin: Texas Antiquities Committee. Texas Antiquities Committee Publication 6, pp. 119–121.

Ruppé, R. J., 1980. The archaeology of drowned terrestrial sites: a preliminary report. Bureau of Historical Sites and Properties Bulletin 6. Division of Archives, History, and Records Management, Department of State, Tallahassee, Florida, pp. 35–45.

Ruppé, C., and Barstad, J. (eds.), 2002. *International Handbook of Underwater Archaeology*. New York: Kluwer Academic/ Plenum.

Salter, E., Murphy, P., and Peeters, H., 2014. Researching, conserving, and managing submerged prehistory: national approaches and international collaboration. In Evans, A. M., Flatman, J. C., and Flemming, N. C. (eds.), *Prehistoric Archaeology on the Continental Shelf: A Global Review*. New York: Springer, pp. 151–172.

Scally, A., and Durbin, R., 2012. Revising the human mutation rate: implications for understanding human evolution. *Nature Reviews Genetics*, **13**(10), 745–753.

Scuvée, F., and Verague, J., 1988. *Le gisement sous-marin du Palé olithique moyen de l'anse de La Mondrée à Fermanville, Manche*. Cherbourg: CEHP-Littus.

Shennan, I., Long, A. J., and Horton, B. P. (eds.), 2015. *Handbook of Sea-level Research*. Chichester: Wiley.

Skaarup, J., 1980. Undersoisk stenhalder. *Tiddskriftet*, **1**, 3–8.

Soares, P., Trejaut, J. A., Loo, J.-H., Hill, C., Mormina, M., Lee, C. L., Chen, Y. M., Hudjashov, G., Forster, P., Macaulay, V., Bulbeck, D., Oppenheimer, S., Lin, M., and Richards, M. B., 2008. Climate change and post-glacial human dispersals in Southeast Asia. *Molecular Biology and Evolution*, **25**(6), 1209–1218.

Stanford, J. D., Hemingway, R., Rohling, E. J., Challenor, P. G., Medina-Elizalde, M., and Lester, A. J., 2011. Sea-level probability for the last deglaciation: a statistical analysis of far-field records. *Global and Planetary Change*, **79**(3–4), 193–203.

Stanford, D., Lowery, D., Jodry, M., Bradley, B. A., Kay, M., Stafford, T. W., Jr., and Speakman, R. J., 2014. New evidence for a possible Paleolithic occupation of the eastern North American continental shelf at the Last Glacial Maximum. In Evans, A. M., Flatman, J. C., and Flemming, N. C. (eds.), *Prehistoric Archaeology on the Continental Shelf: A Global Review*. New York: Springer, pp. 73–93.

Stein, J. K., 2001. A review of site formation processes and their relevance to geoarchaeology. In Goldberg, P., Holliday, V. T., and Ferring, C. R. (eds.), *Earth Sciences and Archaeology*. New York: Kluwer Academic/Plenum Press, pp. 37–51.

Stright, M. J., 1990. Archaeological sites on the North American continental shelf. In Lasca, N. P., and Donahue, J. (eds.), *Archaeological Geology of North America*. Boulder: Geological Society of America. GSA Centennial Special volume 4, pp. 439–465.

Stringer, C. B., Finlayson, J. C., Barton, R. N. E., Fernández-Jalvo, Y., Cáceres, I., Sabin, R. C., Rhodes, E. J., Currant, A. P., Rodríguez-Vidal, J., Giles-Pacheco, F., and Riquelme-Cantal, J. A., 2008. Neanderthal exploitation of marine mammals in Gibraltar. *Proceedings of the National Academy of Sciences*, **105**(38), 14319–14324.

Tizzard, L., Bicket, A. R., Benjamin, J., and De Loecker, D., 2014. A Middle Palaeolithic site in the southern North Sea: investigating the archaeology and palaeogeography of Area 240. *Journal of Quaternary Science*, **29**(7), 698–710.

TRC Environmental Corporation, 2012. Inventory of archaeological site occurrence on the Atlantic Outer Continental Shelf. BOEM 2012-008. New Orleans, Louisiana: U.S. Department of the Interior, Bureau of Ocean Energy Management. www.data.boem.gov/PI/PDFImages/ESPIS/5/5196.pdf.

Veevers, J. J., and van Andel, T. H., 1967. *Morphology and Sediments of the Timor Sea*. Canberra: Bureau of Mineral Resources, Geology and Geophysics. Bulletin, Commonwealth of Australia, Dept. of National Development, Bureau of Mineral Resources, Geology and Geophysics 83.

Weerts, H., Otte, A., Smit, B., Vos, P., Schiltmans, D., Waldus, W., and Borst, W., 2012. Finding the needle in the Haystack by using knowledge of mesolithic human adaptation in a drowning delta. In Bebermeier, W., Hebenstreit, R., Kaiser, E., and Krause, J. (eds.), *Landscape Archaeology. Proceedings of the 2nd International Conference Held in Berlin, 6th–8th June, 2012*. Printed in eTopoi Special volume 3 (2012), pp. 17–24.

Werz, B. E. J. S., and Flemming, N. C., 2001. Discovery in Table Bay of the oldest handaxes yet found underwater demonstrates preservation of hominid artefacts on the continental shelf. *South African Journal of Science*, **97**(5–6), 183–185.

Wessex Archaeology., 2011. *Seabed Prehistory: Site Evaluation Techniques (Area 240) Synthesis. Final Report*. Salisbury: Wessex Archaeology.

Westley, K., and Dix, J., 2006. Coastal environments and their role in prehistoric migrations. *Journal of Maritime Archaeology*, **1**(1), 9–28.

Whitmore, F. C., Jr., Emery, K. O., Cooke, H. B. S., and Swift, D. J. P., 1967. Elephant teeth from the Atlantic continental shelf. *Science*, **156**(3781), 1477–1481.

Wood, W. R., and Johnson, D. L., 1978. A survey of disturbance processes in archaeological site formation. *Advances in Archaeological Method and Theory*, **1**, 315–381.

Yanko-Hombach, V., Gilbert, A. S., Panin, N., Dolukhanov, P. M. (eds.), 2007. *The Black Sea Flood Question: Changes in Coastline, Climate and Human Settlement*. Dordrecht: Springer.

Zhang, W. Y., Harff, J., Schneider, R., and Wu, C., 2010. Development of a modelling methodology for simulation of long-term morphological evolution of the southern Baltic coast. *Ocean Dynamics*, **60**(5), 1085–1114.

Cross-references

Coastal Settings
Harbors and Ports, Ancient
Inundated Freshwater Settings
Paleoshores (Lakes and Sea)
Shell Middens
Shipwreck Geoarchaeology

SUSCEPTIBILITY

Rinita A. Dalan
Department of Anthropology and Earth Science, Minnesota State University Moorhead, Moorhead, MN, USA

Synonyms

Low-field magnetic susceptibility; Magnetic susceptibility

Definition

Magnetic susceptibility. The ratio of the magnetization induced in a sample to the inducing (magnetizing) field.

Volume susceptibility. Magnetic susceptibility expressed as susceptibility per unit volume (κ), dimensionless in SI units.

Mass magnetic susceptibility. Mass-normalized susceptibility (χ) equal to volume susceptibility divided by the density of the sample, in SI units of m^3/kg.

Introduction

Magnetic susceptibility quantifies the degree to which a substance can be magnetized in a weak magnetic field similar to that of the Earth's field – i.e., 5–100 μT (microteslas) – (Banerjee, 1981). This is an easily measured property that is commonly used to assess the concentration of magnetic materials in a sample. Magnetic susceptibility, however, depends not only on the concentration of magnetic grains but also on the composition (magnetic mineralogy) and size of those grains. Grain size refers to the size-dependent magnetic domain state, ranging from thermally unstable ultrafine or superparamagnetic (SP) grains to stable single-domain (SD) and pseudo-single-domain (PSD) grains to large multidomain (MD) grains (Hunt et al., 1995). Magnetic measurements in the laboratory allow an examination of the contribution of magnetic concentration, composition, and grain size to the susceptibility signal.

Magnetic susceptibility techniques are most often applied to soils and sediments, although material studies of artifacts may also include susceptibility measurements. Depending on occupation and firing histories, soils from archaeological sites may exhibit enhanced magnetic properties distinct from surrounding "noncultural" or non-site soils (Tite and Mullins, 1971; Mullins, 1974). Contrasting susceptibilities may permit the definition of sites, activity areas, and features. Understanding how these contrasts relate to changes in magnetic concentration, composition, and grain size may inform studies of formation processes and postdepositional alterations (Dalan and Banerjee, 1998).

Magnetic enhancement

Magnetic enhancement refers to changes in the magnetic mineralogy of upper soil layers that result in higher susceptibility values at the surface as opposed to within subsoil horizons. Enhancement can occur as part of pedogenesis or as a result of naturally occurring or human-generated fires, all of which may convert weakly magnetic oxides and hydroxides to more strongly magnetic forms. Pedogenic enhancement occurs through both low-temperature chemical reactions (i.e., inorganically) as well as organically via magnetotactic bacteria, iron-reducing bacteria, and bacterial-induced chemical reactions (Evans and Heller, 2003). Typically, it is magnetite or maghemite in the superparamagnetic to stable single-domain size range that is produced.

Mass magnetic susceptibilities of common environmental materials range from <0.001 to $>30 \times 10^{-6}$ m^3/kg, which represents a five to six order of magnitude range. Topsoil susceptibilities are generally in the $0.01–14 \times 10^{-6}$ m^3/kg range, and burned soils lie in the $0.2–80 \times 10^{-6}$ m^3/kg range (Dearing, 1999, 36). Measurements of unheated soils from 54 Northern Hemisphere sites yielded an average value of about 1×10^{-6} m^3/kg (Maher and Thompson, 1995), while a survey of heated soils from 60 Bulgarian sites documented susceptibility values of up to 10×10^{-6} m^3/kg (Jordanova et al., 2001). Heating experiments on soils from archaeological sites have shown a range of enhancement factors, with some more than 100 times the original soil susceptibility (Tite and Mullins, 1971; Linford and Canti, 2001).

The magnetic enhancement process is both conservative and environmentally sensitive (Maher, 1986). Enhanced soils will persist unless they are gleyed (waterlogging leading to the reduction of iron to a soluble oxide that can be transported away), or the iron minerals are reduced in some other way. Because topsoils may retain an enhanced susceptibility signal even when buried, susceptibility studies can aid in the search for buried archaeological sites. Magnetic enhancement is dependent on the type of material in which the soils form, the time over which enhancement has been allowed to proceed, climatic variables such as precipitation and temperature, the landform in which the soil develops, and the plant and animal (including human) life on and in the soil. All these environmental influences may be investigated via soil magnetic studies of the end products of the enhancement process.

Humans directly influence the degree of enhancement in a number of ways. They alter properties such as soil temperature, soil chemistry, and soil porosity. They can increase organic matter, expose soils to high temperatures through firing, and incorporate fired or other high-susceptibility materials into the soil matrix. In addition, humans redistribute soils and sediments, both horizontally and vertically in such a way as to produce susceptibility contrasts. For example, if a ditch or pit is excavated into a subsoil with low susceptibility, after which the concavity is filled with a magnetically enhanced topsoil, a high-susceptibility feature will result. The distribution of enhanced soils can yield information on the dynamics of archaeological terrains.

Frequency dependence of susceptibility

A companion property is the frequency dependence of susceptibility (χ_{fd}) (Dearing et al., 1996). This is the difference in susceptibility measured at two frequencies differing by a factor of 10 (e.g., 470 Hz and 4,700 Hz). Measurement of χ_{fd} is used to investigate the contribution of thermally unstable ultrafine (SP) magnetic grains, as these show the most pronounced frequency dependence of susceptibility. Due to the delayed response between the application of the magnetic field and the magnetization of these ultrafine grains, a decrease in susceptibility occurs at higher frequencies. An increase in frequency dependence, suggesting an increase in the percentage of ultrafine magnetic grains, in conjunction with an increase in susceptibility, is potentially indicative of a developed soil. Frequency dependence is often expressed as a percentage change, dividing the difference between the low- and high-frequency measurements by the low-frequency value.

Instrumentation

Magnetic susceptibility can be measured both in the field and in the laboratory. Instruments are divided into dual- and single-coil types, and they may also be separated based on the volume that is measured and/or the context of the application. In general, measurements are rapid, economical, and nondestructive, both in magnetic and archaeological terms. Field instruments provide volume susceptibility measurements, while laboratory instruments can be used to normalize susceptibility by mass and to investigate the effects of packing, water, and other inclusions.

Coincident loop instruments are composed of just one coil, with the depth of investigation related to the diameter of the coil. In the field, these instruments are usually directly applied to moderately smooth surfaces. They are used for topsoil measurements or to investigate stratigraphic sections or the walls of excavations. A number of small portable handheld susceptibility meters (e.g., ZH Instruments SM30, the Exploranium KT-9, and the Geologorazvedka PIMV-1M) provide effective penetration depths ranging from 1 to 2–3 cm (Lecoanet et al., 1999). The Bartington Instruments MS2/MS3 system of sensors includes the MS2F and MS2K with similar penetration depths of 1 cm and 2.5 cm, respectively, as well as the larger-diameter MS2D with an effective penetration depth of approximately 10 cm (Dearing, 1999).

In addition to ground surface application, single-coil instruments can be configured to be lowered down an open hole; they are used to investigate contrasts in susceptibility with depth while maintaining a high and constant resolution. Such downhole applications are particularly useful for documenting magnetic enhancement and identifying buried archaeological deposits (Dalan, 2006b). The Bartington MS2H sensor measures magnetic susceptibility down a small-diameter (2.2–2.5 cm) hole over a radial sensing zone of approximately 1.5 cm. In its standard configuration, it allows measurement to 2–3 m in depth, but this can be extended via additional sections of tubing and longer cables. ZH Instruments makes a soil-profiling kappameter called the SM400 designed for application in a 3.6-cm-diameter hole, which allows depths up to 40 cm to be investigated. Downhole applications are difficult in environments where the soil is hard, dry, or sandy or contains stones or large roots. As lateral resolution is limited, multiple downhole measurements must be completed to map the shapes of features or to provide information on broader landscape changes.

Single-coil sensors for laboratory application can be employed to measure individual samples (usually packed in nonmagnetic containers) or whole or split cores. The Bartington MS2/MS3 system includes the MS2B lab sensor for the measurement of susceptibility and the frequency dependence of susceptibility, the MS2C series of loop sensors for volume susceptibility measurements of various diameters of whole cores, and the MS2E surface scanning sensor for high-resolution measurements of split cores.

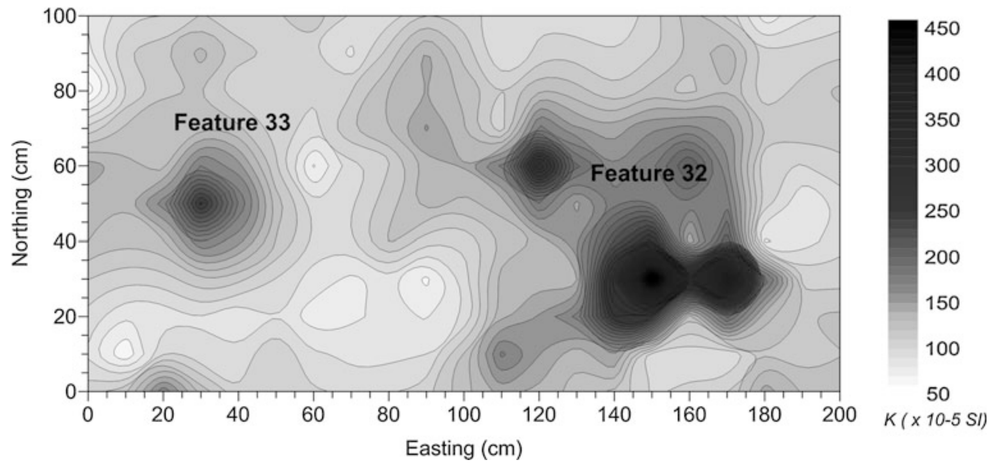
Dual-coil, or slingram, instruments are composed of separate transmitter and receiver coils. Slingram instruments operating in the magnetic susceptibility (i.e., in-phase) mode are less influenced by soil conductivity, and they provide greater penetration depths (but decreased resolution) over single-coil instruments (McNeill, 1986; Tabbagh, 1986; Benech and Marmet, 1999). Effective depths of investigation for slingram instruments used by archaeologists (e.g., the Geonics EM38, the SH3, the CS60, and the CS150) are generally less than 70–80 cm.

Dual-coil downhole options provide opportunities for magnetic susceptibility measurements down larger-diameter holes, although with decreased vertical resolution. For example, the Geonics EM39S, applied down a 5–7.6-cm borehole, has a vertical resolution on the order of a few tenths of a meter (McNeill et al., 1996).

Susceptibility soundings, measured at the surface using the Geonics EM38 (McNeill and Bosnar, 1999), allow a quick estimation of magnetic stratigraphy although the depth of exploration is shallow (approximately 0.5 m) and only a limited number (ca. 3) of magnetic layers may be distinguished. A series of readings is made as the instrument is lowered toward the ground surface from a height of approximately 2 m. Analysis involves comparing the measured and calculated soundings to find the best fit.

Applications

Magnetic susceptibility techniques are broadly applicable (Dalan, 2008). The scale of application ranges from microgeophysical surveys confined to single excavation units, exposures, or core holes to broad investigations of archaeological landscapes. Surveys focus on the location and mapping of archaeological features, activity areas, sites, and cultural and natural soils and landforms. Combined with other soil magnetic and nonmagnetic



Susceptibility, Figure 1 Magnetic susceptibility map of Block 2, 80 cm below datum, Poverty Point State Historic Site. Data collected on a 10-cm grid using a Bartington MS2K sensor. Maps from multiple excavation levels were combined to produce three-dimensional images of the basin-shaped features and to provide data on feature volumes and contrasts useful for comparison to gradiometer surveys. The highest readings correspond to fired-silt artifacts called Poverty Point objects.

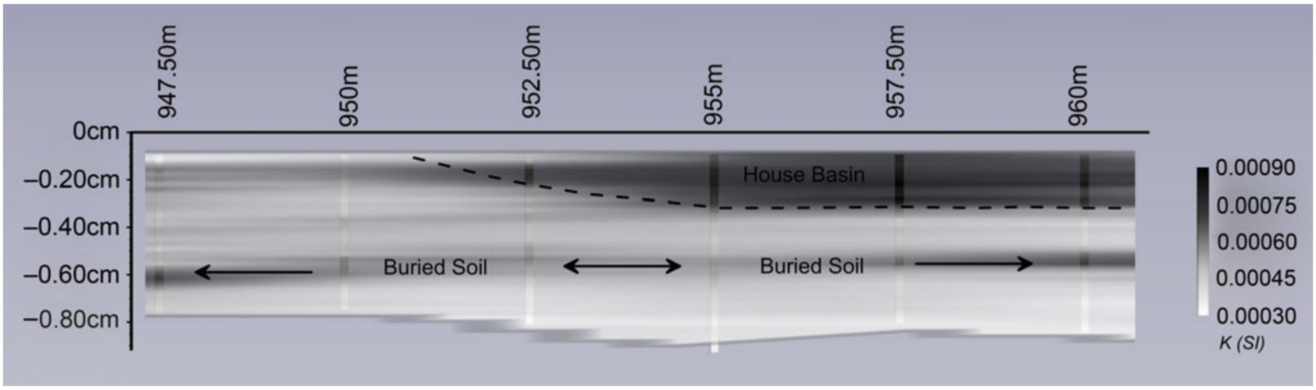
techniques, they can be used to explore site formation and postdepositional processes. Susceptibility studies are often integrated with other geophysical prospection methods such as magnetometry, ground-penetrating radar, resistivity, and electromagnetic conductivity.

Two-dimensional surface maps of magnetic susceptibility are commonly employed in mapping archaeological sites and the features within them. Types of features most frequently investigated are highly magnetic fired features, filled ditches or pits, and other earthen features comprising contrastive soils. Susceptibility instruments can identify subtle features as well as features with gradual boundaries. Susceptibility surveys have also been utilized to identify areas of intense occupation, industrial activity, and agriculturally managed or stockyard soils.

Susceptibility sensors are also employed on exposed sections or excavation walls and floors to identify and map features and even to explore microgeophysical changes within them. These applications integrate changes in geophysical properties with visible and textural changes recorded by excavators. By tracking changes that may be invisible to the excavator, they may also be used to guide and improve excavations. Figure 1 presents an example of a two-dimensional susceptibility map from a 1×2 m excavation unit at the Poverty Point site in Louisiana. *In situ* measurements of volume susceptibility identified features sooner or more clearly than they could be visually identified by excavators (Greenlee, 2009; Dalan and Sharp, 2012). The features shown are basin-shaped pits containing highly magnetic, fired-silt artifacts called Poverty Point objects.

Downhole sensors or susceptibility samples collected by coring allow subsurface features that are beyond the effective depth and resolution of surface sensors to be located, explored, and placed within a stratigraphic context. Thin archaeological horizons at depth or buried paleosols may be mapped by virtue of their enhanced magnetic signal. Susceptibility data sets combining multiple downhole logs or cores, or a series of susceptibility maps at different depths recorded during excavation, provide enhanced opportunities for visualization, including three-dimensional images and animations showing features, use areas, layers, and sites within their cultural and natural contexts (Dalan and Goodman, 2007). Figure 2 provides an exemplary transect of downhole tests across a protohistoric earth lodge at the Biesterfeldt site in North Dakota. Enhanced susceptibility values revealed the presence of a house basin as well as a buried soil (Dalan et al., 2007, 2011). This house was located in a portion of the village that had been plowed during historic times; in this area, neither geophysical surveys conducted at the surface nor topographic changes were effective in identifying earth lodge locations.

Vertical measurements of susceptibility are also useful for examining the effects of postdepositional processes such as soil creep and soil wash. As erosional processes alter spatial patterns of topsoil depth and particle size distributions, patterns in the depth and character of magnetic enhancement can be used to trace relative topsoil-subsoil movements along a slope (Dearing et al., 1985, Dearing et al., 1986; Thompson and Oldfield, 1986). Not only can susceptibility studies be used to identify areas of stability, erosion, and deposition, but this information can even be used to determine the original form of archaeological landscapes or features (Dalan, 2006a). Magnetic susceptibility studies of lake and bog cores, in conjunction with palynological investigations, shed light on erosional histories related to human land use (deforestation, agriculture, and burning) or climate change (Thompson and Oldfield, 1986; Evans and Heller, 2003).



Susceptibility, Figure 2 Cross section along the N914 transect, constructed from downhole tests at six locations spaced 2.5 m apart. Data collected using the Bartington MS2H sensor, with susceptibility values recorded at 2-cm depth increments within each hole. Enhanced susceptibility values distinguish (the western portion of) a shallow earth lodge basin as well as an underlying paleosol.

Magnetic susceptibility surveys are commonly used in conjunction with other geophysical methods (Clark, 1996; Gaffney and Gater, 2003). They often play a supportive role in prediction and preliminary assessment. For example, documenting contrasts in susceptibility between archaeological features and surrounding soils is helpful in evaluating whether a magnetometer survey will work in a given situation, as susceptibility contrasts (alone or in combination with magnetic remanence) produce magnetic anomalies. They are also used to track susceptibility trends across a site, targeting areas for subsequent geophysical work using other methods. They can be used to confirm the presence of an anomaly found by other surveys. Susceptibility contrasts can be used to model the depths and dimensions of magnetic anomalies. Susceptibility studies are also partnered with magnetic measurements accomplished in the laboratory to understand how geophysical anomalies are produced. For example, where surface geophysical surveys have given poor results, soil magnetic studies may shed light on the processes responsible. They have also been used to search for distinctive signatures of archaeological features and anthropogenic soils.

Summary

Magnetic susceptibility is one of a number of geophysical prospection methods used to explore and map archaeological sites. The contribution of this method, however, lies not just in its use as a survey technique but also in its role in exploring questions relating to the formation of the archaeological record and postdepositional alterations.

Just as one would not attempt to characterize a particular soil by examining only one horizon, susceptibility data cannot be fully interpreted without information on how susceptibility varies with depth. Susceptibility sensors designed to be used in excavations and on other exposed surfaces, downhole instruments, and laboratory studies of collected samples extend this method beyond standard surface prospection applications. Vertical measurements can be combined with surface maps for three-dimensional visualization.

As magnetic enhancement is linked to soil formation, investigations of susceptibility and other magnetic properties allow an understanding of the various soil-forming factors, including parent material, climate, topography, time, and living organisms. There is a direct link between human activities and susceptibility through human impacts on the soil environment. In combination with other soil magnetic techniques, susceptibility studies provide an avenue for examining the process of magnetic enhancement and also for tracking the effects of erosion and human earthmoving activities on the archaeological record.

The interpretive potential of susceptibility studies has made them a popular complement to other geophysical methods, in particular electromagnetic conductivity and magnetometer surveys. They are used to assess the potential for magnetometer surveys, separate induced and remanent magnetic components, confirm and interpret anomalies, and generate comparative magnetic models. As many susceptibility instruments investigate volumes similar in size to those analyzed for other physical and chemical properties, susceptibility data are also easily integrated within geoarchaeological studies focused on chemical and physical characterizations of soils and sediments.

Bibliography

Banerjee, S. K., 1981. Experimental methods of rock magnetism and paleomagnetism. In Saltzman, B. (ed.), *Advances in Geophysics*. New York: Academic, Vol. 23, pp. 25–99.

Benech, C., and Marmet, E., 1999. Optimum depth of investigation and conductivity response rejection of the different electromagnetic devices measuring apparent magnetic susceptibility. *Archaeological Prospection*, **6**(1), 31–45.
Clark, A. J., 1996. *Seeing Beneath the Soil: Prospecting Methods in Archaeology*. London: B. T. Batsford. Rev. ed.
Dalan, R. A., 2006a. Magnetic susceptibility. In Johnson, J. K. (ed.), *Remote Sensing in Archaeology: An Explicitly North American Perspective*. Tuscaloosa: The University of Alabama Press, pp. 161–203.
Dalan, R. A., 2006b. A geophysical approach to buried site detection using down-hole susceptibility and soil magnetic techniques. *Archaeological Prospection*, **13**(3), 182–206.
Dalan, R. A., 2008. A review of the role of magnetic susceptibility in archaeogeophysical studies in the USA: recent developments and prospects. *Archaeological Prospection*, **15**(1), 1–31.
Dalan, R. A., and Banerjee, S. K., 1998. Solving archaeological problems using techniques of soil magnetism. *Geoarchaeology*, **13**(1), 3–36.
Dalan, R. A., and Goodman, D., 2007. Imaging buried landforms using down-hole susceptibility data and three-dimensional GPR visualization software. *Archaeological Prospection*, **14**(4), 273–280.
Dalan, R. A., and Sharp, J., 2012. *Magnetic Susceptibility Studies in Excavation Blocks 1–4*. Unpublished report submitted to the Poverty Point Station Archaeology Program, Epps, LA. Moorhead: Department of Anthropology and Earth Science, Minnesota State University Moorhead.
Dalan, R. A., Holley, G. R., Michlovic, M., Gooding, E., and Watters, H., Jr., 2007. Comprehensive Significance Study of the Biesterfeldt Site (32RM1), Ransom County, North Dakota. Unpublished report submitted to the Midwest Archeological Center, National Park Service, Lincoln, NE. Moorhead: Department of Anthropology and Earth Science, Minnesota State University Moorhead.
Dalan, R. A., Bevan, B. W., Goodman, D., Lynch, D., De Vore, S., Adamek, S., Martin, T., Holley, G., and Michlovic, M., 2011. The measurement and analysis of depth in archaeological geophysics: tests at the Biesterfeldt Site, USA. *Archaeological Prospection*, **18**(4), 245–265.
Dearing, J. A., 1999. *Environmental Magnetic Susceptibility: Using the Bartington MS2 System*, 2nd edn. Kenilworth: Chi Publishing.
Dearing, J. A., Maher, B. A., and Oldfield, F., 1985. Geomorphological linkages between soils and sediments: the role of magnetic measurements. In Richards, K. S., Arnett, R. R., and Ellis, S. (eds.), *Geomorphology and Soils*. London: Allen and Unwin, pp. 245–266.
Dearing, J. A., Morton, R. I., Price, T. W., and Foster, I. D. L., 1986. Tracing movements of topsoil by magnetic measurements: two case studies. *Physics of the Earth and Planetary Interiors*, **42** (1–2), 93–104.
Dearing, J. A., Dann, R. J. L., Hay, K., Lees, J. A., Loveland, P. J., Maher, B. A., and O'Grady, K., 1996. Frequency-dependent susceptibility measurements of environmental materials. *Geophysical Journal International*, **124**(1), 228–240.
Evans, M. E., and Heller, F., 2003. *Environmental Magnetism: Principles and Applications of Enviromagnetics*. Amsterdam: Academic.
Gaffney, C. F., and Gater, J., 2003. *Revealing the Buried Past: Geophysics for Archaeologists*. Stroud: Tempus.
Greenlee, D. M., 2009. 2009 Annual report of the station archaeology program at the poverty point state historic site. Unpublished report submitted to the Division of Archaeology, Louisiana Department of Cultural, Recreation and Tourism, Baton Rouge, LA. Monroe: Department of Geosciences, University of Louisiana at Monroe.
Hunt, C. P., Moskowitz, B. M., and Banerjee, S. K., 1995. Magnetic properties of rocks and minerals. In Ahrens, T. J. (ed.), *Rock Physics and Phase Relations: A Handbook of Physical Constants*. Washington, DC: American Geophysical Union. AGU Reference Shelf, Vol. 3, pp. 189–204.
Jordanova, N., Petrovsky, E., Kovacheva, M., and Jordanova, D., 2001. Factors determining magnetic enhancement of burnt clay from archaeological sites. *Journal of Archaeological Science*, **28**(11), 1137–1148.
Lecoanet, H., Lévêque, F., and Segura, S., 1999. Magnetic susceptibility in environmental applications: comparison of field probes. *Physics of the Earth and Planetary Interiors*, **115**(3–4), 191–204.
Linford, N. T., and Canti, M. G., 2001. Geophysical evidence for fires in antiquity: preliminary results from an experimental study. *Archaeological Prospection*, **8**(4), 211–225.
Maher, B. A., 1986. Characterisation of soils by mineral magnetic measurements. *Physics of the Earth and Planetary Interiors*, **42**(1–2), 76–92.
Maher, B. A., and Thompson, R., 1995. Paleorainfall reconstructions from pedogenic magnetic susceptibility variations in the Chinese loess and paleosols. *Quaternary Research*, **44**(3), 383–391.
McNeill, J., 1986. *Geonics EM38 Ground Conductivity Meter: Operating Instructions and Survey Interpretation Techniques*. Mississauga: Geonics Limited. Technical Note TN-21.
McNeill, J., and Bosnar, M., 1999. *Application of "Dipole-Dipole" Electromagnetic Systems for Geological Depth Sounding*. Mississauga: Geonics Limited. Technical Note TN-31.
McNeill, J. D., Hunter, J. A., and Bosnar, M., 1996. Application of a borehole induction magnetic susceptibility logger to shallow lithological mapping. *Journal of Environmental and Engineering Geophysics*, **1**(B), 77–90.
Mullins, C. E., 1974. The magnetic properties of the soil and their application to archaeological prospecting. *Archaeo-Physika*, **5**, 143–347.
Tabbagh, A., 1986. Applications and advantages of the slingram electromagnetic method for archaeological prospecting. *Geophysics*, **51**(3), 576–584.
Thompson, R., and Oldfield, F., 1986. *Environmental Magnetism*. London: Allen and Unwin.
Tite, M. S., and Mullins, C. E., 1971. Enhancement of the magnetic susceptibility of soils on archaeological sites. *Archaeometry*, **13**(2), 209–219.

Cross-References

Archaeological Stratigraphy
Data Visualization
Electrical Resistivity and Electromagnetism
Geophysics
Ground-Penetrating Radar
Hearths and Combustion Features
Landscape Archaeology
Magnetometry for Archaeology
Poverty Point Site, Louisiana
Remote Sensing in Archaeology
Site Formation Processes
Soil Stratigraphy

SWANSCOMBE

Tom S. White
Research Laboratory for Archaeology and the History of Art, University of Oxford, Oxford, UK

Definition

Swanscombe is an internationally famous Middle Pleistocene locality in the Lower Thames Valley, UK. It is dated to the Hoxnian Interglacial of Britain, which corresponds in time to the Holsteinian Interglacial of northern Europe and the Mindel-Riss Interglacial of the Alpine ice age chronology, with a date within Marine Isotope Stage (MIS) 11 (424–374 ka). The various Swanscombe sites have yielded rich archaeological and paleontological assemblages, and it remains a flagship site for NW European Quaternary studies after over a century of research.

Introduction

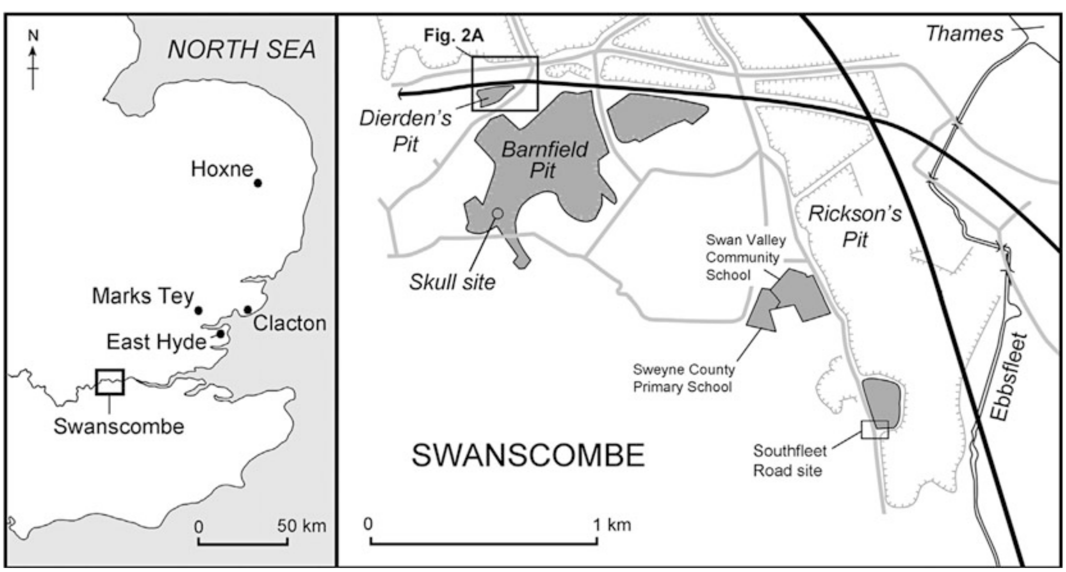
The sand and gravel pits in the vicinity of Swanscombe, Kent, have been the subject of geoarchaeological research since the nineteenth century. The Swanscombe quarries (Figure 1), many of which were subsequently deepened and obliterated as a result of chalk extraction for the cement industry, revealed a complex of gravels, sands, and silts (loams). These strata form part of the Boyn Hill terrace of the River Thames, which is preserved in the Swanscombe area overlapping a remnant of the Paleocene Thanet Sand, which itself rests atop Cretaceous Chalk.

The most important site is Barnfield Pit, where the famous hominin skull was found. The skull has often been attributed to *Homo heidelbergensis* but is now usually regarded as an early member of the Neanderthal lineage (Stringer and Hublin, 1999). The circumstances of its discovery are themselves remarkable; two parts of the cranium (the right parietal and occipital) were recovered in the mid-1930s by a local dentist, Alvan T. Marston, but it was 20 years later when the third refitting part, the left parietal, was found by John Wymer during his 1955 excavation. These discoveries led to Barnfield Pit becoming a Site of Special Scientific Interest (SSSI) and a National Nature Reserve (NNR). Also critical to understanding the Swanscombe sequence are exposures recorded at Dierden's Pit, where optimal preservation of calcareous fossils provided an unparalleled paleoenvironmental and biostratigraphic record (Kerney, 1959; Sutcliffe, 1964; White et al., 2013), and Rickson's Pit, now lost to chalk quarrying and landfill, but once exposing the most complete Swanscombe sequence other than at Barnfield Pit (Dewey, 1932; Wymer, 1968; Bridgland, 1994).

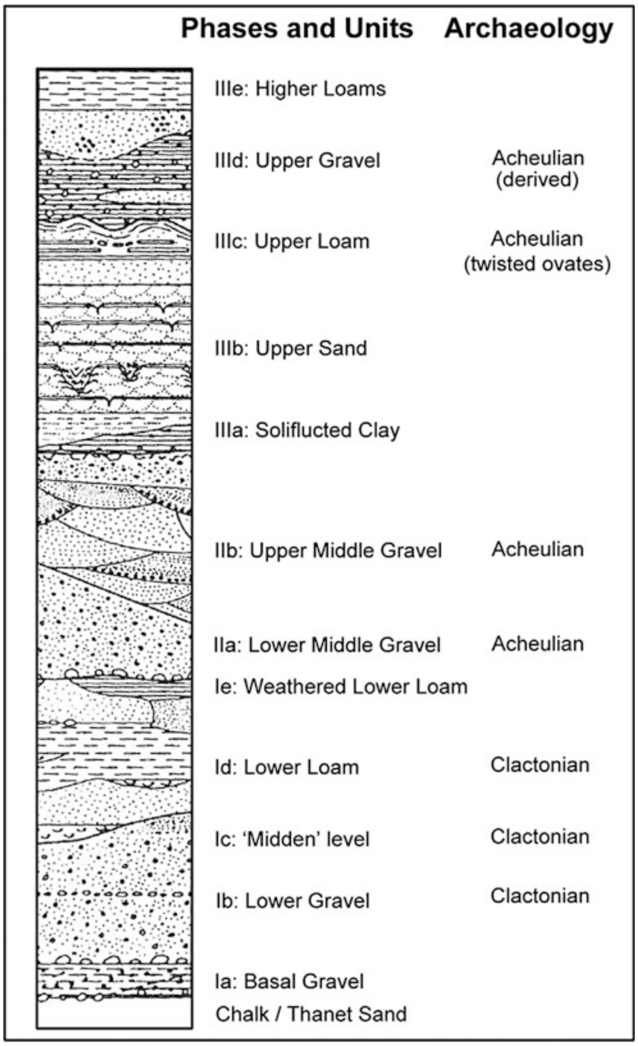
Most recently, research in association with major construction projects has extended our knowledge and understanding of the Swanscombe sequence, particularly during the building of HS1, the high-speed railway linking London with the Channel Tunnel, which revealed laterally equivalent deposits that represent a south-bank tributary system just upstream of its contemporary confluence with the Thames (Wenban-Smith et al., 2006; Wenban-Smith, 2013).

Stratigraphy

The definitive Swanscombe stratigraphy (Figure 2) follows that of Bernard Conway (Conway and Waechter, 1977; Conway, 1996), who made use of surviving exposures that were soon to be concealed or destroyed to establish a more complete sequence than can be observed at



Swanscombe, Figure 1 Maps showing the location of Swanscombe in the Lower Thames Valley and important localities in the Swanscombe area mentioned in the text (Modified from White et al., 2013).



Swanscombe, Figure 2 The stratigraphic and archaeological sequence at Barnfield Pit, Swanscombe (After Bridgland, 1994; Conway et al., 1996).

present in the NNR. Its lithostratigraphic division and hierarchy follows Bridgland (1994). Three subdivided phases are numbered I to III, from bottom to top.

The Phase I deposits at Swanscombe are of restricted occurrence, having been laid down in a paleochannel that was more constricted than the Thames floodplain that existed later in the sequence. The main divisions are the Lower Gravel (Ib) and the Lower Loam (Id); the more localized beds Ia and Ic should be regarded as components of the Lower Gravel, whereas Ie is the weathered upper part of the Lower Loam (Kemp, 1985). The basal clayey bed Ia has been attributed to solifluction during the cold late Anglian glaciation (MIS 12); otherwise, the Lower Gravel consists of bedded sandy medium-coarse gravel, fining upward to shelly sands and fine gravels. Although Waechter et al. (1969) coined the term "midden" for bed Ic, A. P. Currant (in Conway et al., 1996) interpreted it as a naturally fossiliferous channel-fill deposit. The Lower Loam, which is the infilling of an even narrower channel cut into the top of the Lower Gravel, comprises horizontally bedded clayey sands with thin lenses of shelly sand and evidence for channel cuts and fills. Vertical changes in the lithology, together with lithic knapping scatters from hominin tool-making activities and surfaces with animal footprints, suggest intermittent sedimentation and drying out, perhaps in keeping with its interpretation as an overbank floodplain deposit of generally fine alluvial sediments.

The Lower Middle Gravel (IIa) and Upper Middle Gravel (IIb) members of Phase II are considerably more widespread than the Phase I deposits, occurring in several pits such as at Craylands Lane, where they overlay bedrock, Dierden's Pit (White et al., 2013), and Southfleet Road (Wenban-Smith and Bridgland, 2001). The Phase II deposits represent the MIS 11 (Hoxnian Interglacial), however, so they are not coeval with the widespread outcrop of the Boyn Hill Gravel, which is generally of cold-climate (MIS 10) origin (cf. Bridgland, 2006). The Lower Middle Gravel consists of up to 2.5 m of medium-coarse sandy gravel, with a coarser lag deposit at the base, whereas the more variable Upper Middle Gravel is generally much finer, typically consisting of cross-bedded and ripple-laminated sands with thin gravels and silty clays. As a whole, the Middle Gravels can perhaps be interpreted as a typical upward-fining fluvial sequence, although an erosional contact has been observed between the two members (e.g., Wymer, 1968). These are the deposits in which the celebrated Rhenish molluscan fauna appears, as does the Acheulian Paleolithic industry (with hand axes); the Swanscombe skull was recovered from the basal part of bed IIb.

In many ways, the transition into the Phase III deposits appears to be a continuation of the fining upward sequence observed in Phase II, with the thick Upper Loam (IIIc) representing further floodplain (overbank) sedimentation. However, the localized beds IIIa and IIIb, which were recorded by Conway (1996) from the northwestern part of Barnfield Pit, have been attributed to a much colder climate, the former (IIIa) being regarded as the product of solifluction, whereas the latter (IIIb) contained structures interpreted as ice-wedge casts. This is in keeping with paleontological evidence for climatic cooling from the uppermost Phase II deposits, which some claim show evidence of cryoturbation. In contrast, the Upper Loam has been likened to an estuarine deposit, based purely on its sedimentological characteristics, which would imply a warm climate and high sea level. Unfortunately, the Upper Loam and the uppermost Swanscombe sediments in general are oxidized and decalcified and have therefore produced no faunal evidence to corroborate or reject this sedimentological interpretation. Indeed, Conway (1996) interpreted the Upper Loam as a warm-climate deposit, suggesting that it represented MIS 9, in contrast to the MIS 11 age of the Phase I and II deposits.

Schreve (2001a, b), while accepting Conway's climatic interpretation, preferred to assign these upper warm-climate sediments to a later temperate substage of MIS 11 (MIS 11a), an interpretation that was upheld by later work at Dierden's Pit (White et al., 2013).

The final widespread deposit at Swanscombe, the Upper Gravel (IIId), is interpreted as soliflucted overburden during MIS 10; from 0.9 to 1.6 m in thickness, it consists of fine to medium gravel clasts in a sandy clay matrix and has deformed ice-wedge casts as well as, in one of Conway's (1996) sections, a raft of Upper Loam. A highly localized "Higher Loam" (IIIe) has also been recorded, restricted to the southwestern part of the site; it is a horizontally bedded clayey sand with scattered pebbles, perhaps a slopewash (colluvial) deposit.

Paleontology

The various exposures at Swanscombe have yielded many important fossil assemblages, notably vertebrates, mollusks, and ostracods. These have been central to the development of biostratigraphic schemes (e.g., Schreve, 2001a; Schreve, 2001b; White et al., 2013) and the correlation of the Swanscombe sequence with other Hoxnian localities (cf. Kerney, 1971), especially given that pollen is so poorly preserved at Swanscombe. The most recent paleontological research at Swanscombe has focused on non-marine mollusk and ostracod successions from Dierden's Pit, which has shed light on several important issues. First, they provide both a firm basis for correlations with other critical sections at Swanscombe and a secure context for the occurrence of Acheulian archaeological assemblages at Dierden's Pit (see below). Second, they establish a pattern of colonization by the biostratigraphically important "Rhenish" suite of freshwater mollusks, demonstrating that these did not appear in the Lower Thames simultaneously but in an ordered sequence (White et al., 2013). Third, they clarify aspects of the sea-level history in the Lower Thames during the Hoxnian (see below). Fourth, the ostracod assemblages provide the basis for quantitative estimates of paleoclimate using the Mutual Ostracod Temperature Range (MOTR) method.

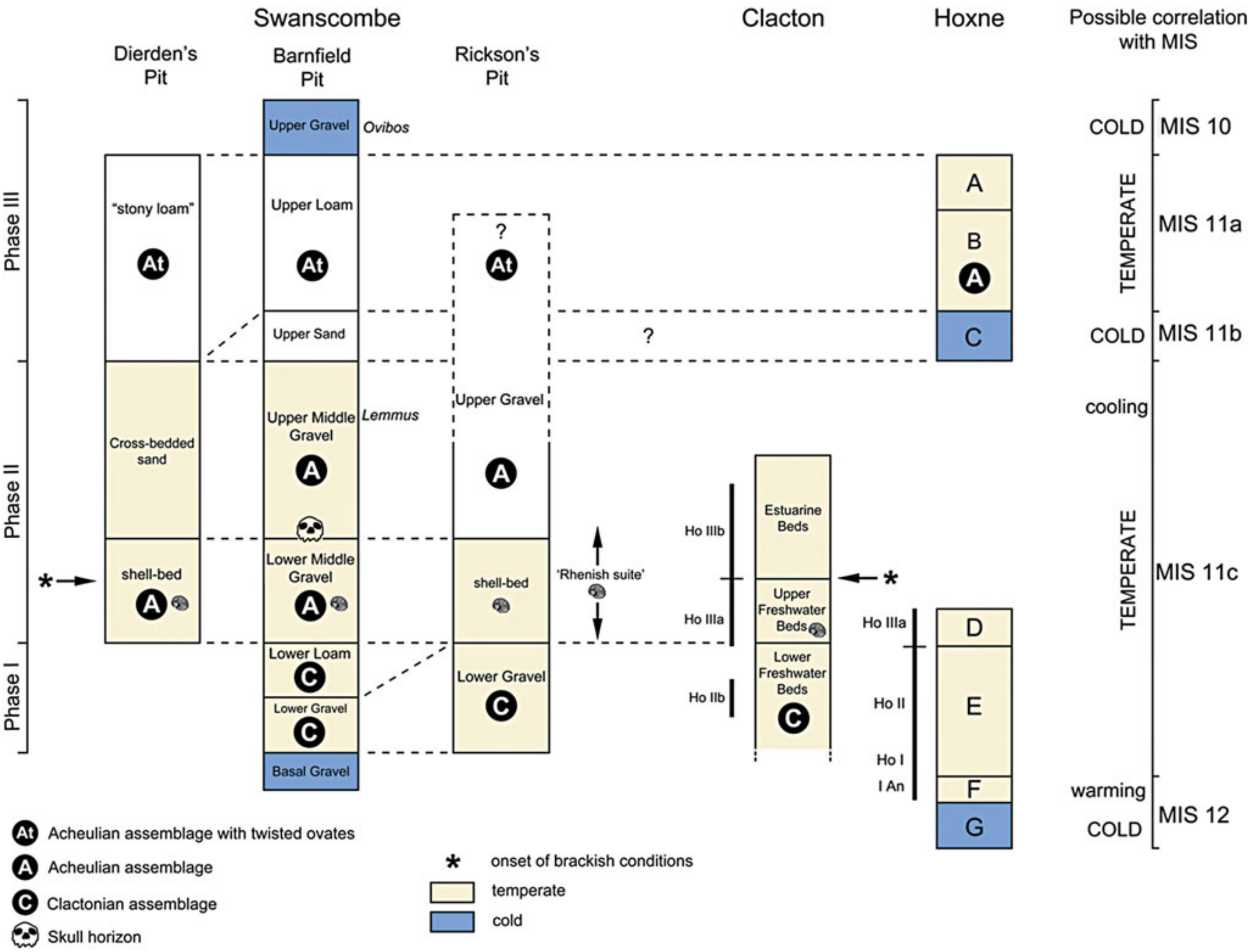
Evidence for sea-level change at Swanscombe

Brackish indicator fossils have previously been reported from Swanscombe in the form of a vertebra of bottlenose dolphin, *Tursiops truncatus* (Sutcliffe, 1964), occasional shells of hydrobiid mollusks (Kerney, 1971), and otoliths of European smelt, *Osmerus eperlanus* (Stinton, 1985). This brackish signal can now be augmented by the occurrence of the ostracod *Cyprideis torosa* (White, 2012; White et al., 2013), which characterizes the upper part of the Dierden's Pit sequence and provides a record for both the onset and strength of brackish conditions in the Swanscombe reach of the Hoxnian Thames. If the above correlations are secure, the first appearance of *Cyprideis torosa* at Swanscombe coincided with pollen substage Ho IIIa (the Hoxnian Glacial Stage is divided into four substages Ho I to Ho IV) but suggests salinities of no more than 5 ‰ (cf. Meisch, 2000; van Harten, 2000). Study of the geochemical composition of ostracod valves has provided quantitative estimates of paleosalinity at Swanscombe, confirming the minimal influence of marine waters there (White, 2012). The evidence from Dierden's Pit provides an index point for the onset of brackish conditions in the Thames and confirms that a single marine transgression can be recognized within the Swanscombe sequence.

Archaeology

Swanscombe is justly famous for its important Paleolithic record, in which Acheulian assemblages, with different types of hand axes, occur stratigraphically above deposits that have yielded a Clactonian industry (e.g., Wymer, 1968; Conway et al., 1996). This celebrated instance of Paleolithic stratification has now been supplemented with the occurrence of twisted ovate hand axes in the upper (Phase III) division of the Swanscombe sequence, whereas the middle division (Phase II) is characterized by pointed hand axes (Figures 2 and 3). Evidence from Dierden's Pit addresses some outstanding issues in the interpretation of this record. The earliest archaeological discoveries from Dierden's Pit were sharp, patinated hand axes, reportedly recovered directly from the shell bed indicated in Figure 3 as lower Phase II coeval with the Lower Middle Gravel in Barnfield Pit (Stopes, 1900, 1904; Newton, 1901; Kennard, 1916; Kerney, 1959; Wenban-Smith, 2007). However, the stratigraphic context for these Acheulian assemblages was thrown into doubt by subsequent work conducted by Smith and Dewey (1914), who failed to recover any hand axes within an assemblage of over 500 cores and flakes. This assemblage was therefore considered to be Clactonian by some authors (e.g., Wymer, 1999; McNabb, 2007), and because it was derived from the base of a "loamy pocket," it was thought to postdate the shell bed, which was consequently correlated with the Barnfield Pit Lower Gravel (Smith and Dewey, 1914; Wymer, 1999; McNabb, 2007). However, an assemblage of ∼100 cores and flakes from Dierden's Pit, some of which were identified as hand axe-thinning flakes, was recovered during the 1950s from an exposure previously examined by Smith and Dewey (Kerney, 1959). The presence of thinning flakes suggests that although the Dierden's Pit assemblages lack hand axes, they are indeed Acheulian.

Little attention has been paid to the deposits recorded above the shell bed in the southern part of Dierden's Pit, from which archaeological material was also recovered. Here, the shell bed was truncated by current-bedded sands (Figure 3) that are considered to be a probable equivalent of the sandy Upper Middle Gravel at Barnfield Pit. Above these sands a "stony loam" was recorded in the uppermost parts of Smith and Dewey's sections A, B, and D, which might therefore be equivalent to the Upper Loam at Barnfield Pit. The hand axes collected by Henry Stopes from the Dierden's Pit shell bed are typologically similar



Swanscombe, Figure 3 Correlation of the important sections at Swanscombe. Note the superposition of Acheulian over Clactonian archaeological assemblages and the later occurrence of twisted ovate hand axes. Units for which there is clear sedimentological or paleontological evidence for the prevailing climate are color-coded. Tentative correlations with the Marine Isotope Stages (*MIS*) of the deep sea record are also shown (Modified from White et al., 2013).

to those recovered in far greater numbers from the Lower Middle Gravel at Barnfield Pit (Wenban-Smith, 2009). However, the assemblage collected by W. M. Newton comprises mostly cordate and sharp, twisted ovate hand axes typical of the Upper Loam at Barnfield Pit. The occurrence of assemblages with a significant proportion of twisted ovates has been assigned to the later part of the Hoxnian (MIS 11) (White, 1998; Bridgland and White, 2014). Assemblages rich in twisted ovates have also been used as a tentative indication of an approximate MIS 11 age for the Old Milton Gravel of the River Solent, which lacks other fossil remains (Westaway et al., 2006). An important observation is that the twisted ovates from Dierden's Pit were reportedly recovered from the south side of the site at a depth of only ~1 m below the topsoil (F. Corner, in Smith and Dewey, 1914). This suggests that the twisted ovates were recovered from the "stony loam" overlying the shell bed; whether or not this represents an equivalent to the Upper Loam at Barnfield Pit remains to be seen, but it is here considered a strong possibility and a connection that has not previously been made (cf. White et al., 2013).

The archaeological succession known from Barnfield Pit has parallels at two other Swanscombe localities: Rickson's Pit (Wymer, 1968) and the Southfleet Road elephant butchery site (Wenban-Smith et al., 2006). At Rickson's Pit (Figure 3), a basal unit of coarse gravel yielded a large assemblage (~680) of cores and flakes (Chandler, 1932; Dewey, 1932; Roe, 1968a) considered to be Clactonian by McNabb (2007). This was overlain by a shell bed containing *Theodoxus* and *Corbicula* (Chandler, 1932; Dewey, 1932) that yielded ~45 hand axes (Roe, 1968a, 184) – assuming that the Middle Gravel at Rickson's Pit (sensu Roe, 1968b) is the same as the "shell bed" (bed c) of Dewey (1932). Above this, Dewey (1932) recorded an "even-bedded ochreous sand" ("brickearth" of Roe, 1968a) that yielded 12 hand axes and an upper unit of current-bedded sand and gravel from which ovate hand axes in fresh condition were obtained (Dewey, 1932, 1959; Roe, 1968a). McNabb (2007), following Dewey (1932, 1959), considered both the basal gravel and the shell bed at Rickson's Pit to be equivalent to the Lower Gravel at Barnfield Pit, on the basis of the absence of hand axes from these units. However, this correlation ignores the occurrence of "Rhenish" elements (Figure 3) in the molluscan fauna from the Rickson's Pit shell bed (Davis, 1953; Kerney, 1959; Castell, 1964), which indicates correlation with the Dierden's Pit shell bed and the Barnfield Pit Lower Middle Gravel. Moreover, the occurrence of all of the "Rhenish" species except *Viviparus diluvianus* suggests that the Rickson's Pit shell bed corresponds with molluscan biozone 4 of the Dierden's Pit sequence (see above). The molluscan assemblage from Rickson's Pit therefore provides the best evidence for relating this site with other Swanscombe localities.

The Southfleet Road site is located to the south of the other Swanscombe localities (Figure 1) and represents a tributary of the Thames. Here, the articulated remains of a straight-tusked elephant (*Palaeoloxodon antiquus*) were discovered within a gray clay, in association with a Clactonian artifact assemblage (Wenban-Smith et al., 2006; Wenban-Smith, 2013). This clay was overlain by sands and gravels containing mostly rolled hand axes. Although no molluscan remains were recovered in direct association with the elephant, shells were found within a calcareous channel fill from which struck flakes were also recovered. The molluscan fauna was similar to that recovered from the Lower Loam at Barnfield Pit and lacked any of the "Rhenish" species or those indicative of closed-canopy woodland known from the Lower Middle Gravel at Dierden's Pit. The archaeological and molluscan records from Southfleet Road are therefore consistent with those from Barnfield Pit and Rickson's Pit (White et al., 2013).

Bibliography

Bridgland, D. R., 1994. *Quaternary of the Thames*. London: Chapman & Hall. The Geological Conservation Review Series, 7.

Bridgland, D. R., 2006. The Middle and Upper Pleistocene sequence in the Lower Thames: a record of Milankovitch climatic fluctuation and early human occupation of southern Britain: Henry Stopes Memorial Lecture 2004. *Proceedings of the Geologists' Association*, **117**(3), 281–305.

Bridgland, D. R., and White, M. J., 2014. Fluvial archives as a framework for the Lower and Middle Palaeolithic: patterns of British artefact distribution and potential chronological implications. *Boreas*, **43**(2), 543–555.

Castell, C. P., 1964. The non-marine Mollusca. In Ovey, C. D. (ed.), *The Swanscombe Skull. A Survey of Research on a Pleistocene Site*. London: Royal Anthropological Institute of Great Britain and Ireland, pp. 77–83.

Chandler, R. H., 1932. The Clactonian Industry and report of field meeting at Swanscombe (II), June 13th, 1931. *Proceedings of the Geologists' Association*, **43**(1), 70–72.

Conway, B., 1996. The geology outside the National Nature Reserve, 1968–72. In Conway, B., McNabb, J., and Ashton, N. (eds.), *Excavations at Barnfield Pit, Swanscombe, 1968–72*. London: Department of Prehistoric and Romano-British Antiquities. British Museum Occasional Paper, 94, pp. 67–88.

Conway, B., and Waechter, J. d'A., 1977. Lower Thames and Medway valleys – Barnfield Pit, Swanscombe. In Shephard-Thorn, E. R., and Wymer, J. J. (eds.), *South East England and the Thames Valley*. Norwich: INQUA, pp. 38–44. Excursion Guide A5, X INQUA Congress, Birmingham. Geoabstracts.

Conway, B., McNabb, J., and Ashton, N. (eds.), 1996. *Excavations at Barnfield Pit, Swanscombe, 1968–72*. London: Department of Prehistoric and Romano-British Antiquities. British Museum Occasional Paper, 94.

Davis, A. G., 1953. On the geological history of some of our snails, illustrated by some Pleistocene and Holocene deposits in Kent and Surrey. *Journal of Conchology*, **23**, 355–364.

Dewey, H., 1932. The Palaeolithic deposits of the Lower Thames. *Quarterly Journal of the Geological Society of London*, **88**, 35–56.

Dewey, H., 1959. *Palaeolithic Deposits of the Thames at Dartford Heath and Swanscombe*. Unpublished text of the Henry Stopes memorial lecture read to the Geologists' Association.

Kemp, R. A., 1985. The decalcified Lower Loam at Swanscombe, Kent: a buried Quaternary soil. *Proceedings of the Geologists' Association*, **96**(4), 343–355.

Kennard, A. S., 1916. The Pleistocene succession in England. *Proceedings of the Prehistoric Society of Eastern Anglia*, **2**, 249–267.

Kerney, M. P., 1959. *Pleistocene Non-marine Mollusca of British Interglacial Deposits*. Unpublished PhD thesis, University of London.

Kerney, M. P., 1971. Interglacial deposits at Barnfield Pit, Swanscombe, and their molluscan fauna. *Journal of the Geological Society of London*, **127**(1), 69–93.

McNabb, J., 2007. *The British Lower Palaeolithic: Stones in Contention*. London: Routledge.

Meisch, C., 2000. *Süßwasserfauna von Mitteleuropa 8/3. Crustaceae: Ostracoda*. Heidelberg: Spektrum Akademischer Verlag.

Newton, W. M., 1901. The occurrence in a very limited area of the rudest with the finer forms of worked stones. *Man*, **1**, 81–82.

Roe, D. A., 1968a. British Lower and Middle Palaeolithic Handaxe Groups. *Proceedings of the Prehistoric Society*, **34**, 1–82.

Roe, D. A., 1968b. *A Gazetteer of British Lower and Middle Palaeolithic Sites*. London: Council for British Archaeology. Research Report of the Council for British Archaeology, 8.

Schreve, D. C., 2001a. Differentiation of the British late Middle Pleistocene interglacials: the evidence from mammalian biostratigraphy. *Quaternary Science Reviews*, **20**(16–17), 1693–1705.

Schreve, D. C., 2001b. Mammalian evidence from Middle Pleistocene fluvial sequences for complex environmental change at the oxygen isotope substage level. *Quaternary International*, **79**(1), 65–74.

Smith, R. A., and Dewey, H., 1914. The high terrace of the Thames: report on excavations made on behalf of the British Museum and H. M. Geological Survey in 1913. *Archaeologia*, **65**, 187–212.

Stinton, F., 1985. British Quaternary fish otoliths. *Proceedings of the Geologists' Association*, **96**(3), 199–215.

Stopes, H., 1900. On the discovery of Neritina fluviatilis with a Pleistocene fauna and worked flints in high terrace gravels of the Thames Valley. *Journal of the Royal Anthropological Institute of Great Britain and Ireland*, **29**, 302–303.

Stopes, C., 1904. Palaeolithic implements from the Shelly Gravel Pit at Swanscombe, Kent. In *Report of the 73rd Meeting of the British Association for the Advancement of Science held at Southport in September 1903*. London: John Murray, pp. 803–804.

Stringer, C. B., and Hublin, J.-J., 1999. New age estimates for the Swanscombe hominid, and their significance for human evolution. *Journal of Human Evolution*, **37**(6), 873–877.

Sutcliffe, A. J., 1964. The mammalian fauna. In Ovey, C. D. (ed.), *The Swanscombe Skull. A Survey of Research on a Pleistocene Site*. London: Royal Anthropological Institute of Great Britain and Ireland, pp. 85–111.

van Harten, D., 2000. Variable noding in Cyprideis torosa (Ostracoda, Crustacea): an overview, experimental results and a model from Catastrophe Theory. *Hydrobiologia*, **419**(1), 131–139.

Waechter, J. D.'. A., Newcomer, M. H., and Conway, B. W., 1969. Swanscombe 1969. *Proceedings of the Royal Anthropological Institute of Great Britain and Ireland*, **1969**, 83–93.

Wenban-Smith, F. F., 2007. Stopes Palaeolithic Project: Final Report. English Heritage/Archaeology Data Service.

Wenban-Smith, F. F., 2009. Henry Stopes (1852–1902): engineer, brewer and anthropologist. In Hosfield, R. T., Wenban-Smith, F., and Pope, M. I. (eds.), *Great Prehistorians: 150 Years of Palaeolithic Research, 1859–2009*. London: Lithic Studies Society. Special Volume of *Lithics*, 30, pp. 62–81.

Wenban-Smith, F. F., and Bridgland, D. R., 2001. Palaeolithic archaeology at the Swan Valley Community School, Swanscombe, Kent. *Proceedings of the Prehistoric Society*, **67**, 219–259.

Wenban-Smith, F. (ed.), 2013. *The Ebbsfleet Elephant: Excavations at Southfleet Road, Swanscombe in Advance of High Speed 1, 2003–4*. Oxford Archaeology Monograph, 20. Oxford Archaeology, Oxford

Wenban-Smith, F. F., Allen, P., Bates, M. R., Parfitt, S. A., Preece, R. C., Stewart, J. R., Turner, C., and Whittaker, J. E., 2006. The Clactonian elephant butchery site at Southfleet Road, Ebbsfleet, UK. *Journal of Quaternary Science*, **21**(5), 471–483.

Westaway, R., Bridgland, D. R., and White, M. J., 2006. The Quaternary uplift history of central southern England: evidence from the terraces of the solent river system and nearby raised beaches. *Quaternary Science Reviews*, **25**(17–18), 2212–2250.

White, M. J., 1998. Twisted ovate bifaces in the British Lower Palaeolithic: some observations and implications. In Ashton, N., Healy, F., and Pettitt, P. (eds.), *Stone Age Archaeology: Essays in Honour of John Wymer*. Oxford: Oxbow Books, pp. 98–104.

White, T. S., 2012. *Late Middle Pleistocene Molluscan and Ostracod Successions and their Relevance to the British Palaeolithic Record*. Unpublished PhD thesis, University of Cambridge.

White, T. S., Preece, R. C., and Whittaker, J. E., 2013. Molluscan and ostracod successions from Dierden's Pit, Swanscombe: insights into the fluvial history, sea-level record and human occupation of the Hoxnian Thames. *Quaternary Science Reviews*, **70**, 73–90.

Wymer, J. J., 1968. *Lower Palaeolithic Archaeology in Britain, as Represented by the Thames Valley*. London: John Baker.

Wymer, J. J., 1999. *The Lower Palaeolithic Occupation of Britain*. Salisbury: Wessex Archaeology and English Heritage.

Cross-references

Alluvial Settings
Amino Acid Racemization
Glacial Settings
Paleoenvironmental Reconstruction

T

TELLS

Wendy Matthews
Department of Archaeology, School of Archaeology, Geography and Environmental Science, University of Reading, Reading, UK

Introduction

Tells are archaeological mounds formed by the built-up remains of sequential buildings and deposits from activities and settlement in specific locations within a landscape. These mounds are of particular importance in archaeology and geoarchaeology as they represent not only places of repeated significance and habitation by human communities but also sites in which cultural and bioarchaeological materials are often well preserved due to rapid burial by deposits from subsequent activities and settlement. Tells have often been preferentially selected for archaeological investigation as they are highly visible sites, rising above the surrounding landscape, and they enable study of continuity and change in social and ecological strategies in a particular locale, often over thousands of years, as at Aşıklı Höyük, Turkey (Figure 1). These mounds, however, are only one node and source of evidence in the complex networks, cycles, and histories of communities. Many other sites are less visible and may have been eroded or deeply buried below later sediments and soils.

This examination of the geoarchaeology of tells begins with a review of their geographic and temporal distribution and their history and techniques of geoarchaeological investigation. It then examines key concepts, theories, and ethics in the study of tells before highlighting the wide range of case studies and insights provided by geoarchaeology in the investigation of these important sites. All dates are calibrated BCE.

Tell distribution, structure, and history of investigation

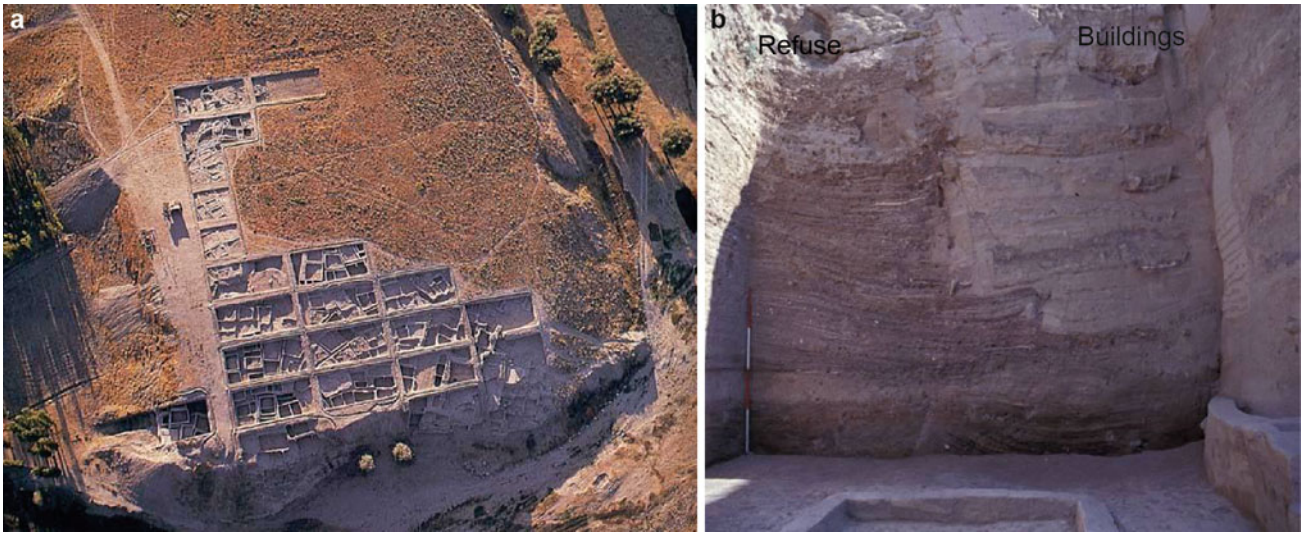
Distribution and structure of tells

The term "tell" is Arabic for mound and is commonly used in archaeology, as here, to refer to settlement mounds in a wide range of regions, including Bulgaria, Hungary, Greece, Turkey, the Levant, Egypt, North Africa, Syria, Iraq, Iran, Pakistan, Afghanistan, and Central Asia. Other common toponyms include "höyük" or "tepe" in Turkish and "chogha" in Farsi. Other types of mounds investigated by geoarchaeological research include shell mounds or middens, burial and/or ceremonial mounds, and accumulated occupation in other regions of the world. Some of the earliest tells began to form when communities became increasingly sedentary with repeated and more extended occupation at particular sites; this process began by at least ca. 12,000 BCE in the Middle East, during global warming at the end of the Pleistocene Ice Age. Tells range in size from <100 m in diameter and 2–3 m high to >1 km across and >40 m high, as at Tell Brak in Syria (Figure 2). They are highly variable in their origin, history of expansion, contraction, and abandonment, as well as in the range of activities and structures represented within them, which may include residential spaces, ritual and monumental buildings, craft and industrial areas, open areas, streets, lanes, and animal pens (Postgate, 1992; Stone, 2013).

History of investigation

Geoarchaeological research on tells began during a period of increasing scientific inquiry and analyses in

A.S. Gilbert (ed.), *Encyclopedia of Geoarchaeology*, DOI 10.1007/978-1-4020-4409-0,



Tells, Figure 1 Neolithic tell, Aşıklı Höyük, Turkey, occupied C 8400–7400 BCE; (**a**) aerial view of tell; (**b**) section showing architectural and refuse deposits (After Esin and Harmankaya, 1999, Figure 4).

Tells, Figure 2 Tell Brak, northeastern Syria, >43 m high, 1 km in length. Site areas discussed in the text are indicated on the aerial view (After Trümpler and Gerster, 2005, Figure 32).

archaeology. Some of the earliest research was conducted by Davidson at the Bronze Age tell of Sitagroi in Greece and published in the first book in archaeology that dealt specifically with geoarchaeology (Davidson and Shackley, 1976). He investigated architectural materials and sources by analyzing their particle size and the impact of human activities on the elemental composition of archaeological deposits by analysis of phosphorus. Butzer (1982) was among the first to review geoarchaeological evidence on the nature and formation of settlement mounds and their correlation with populations and their ecological strategies. One of the first systematic geoarchaeological investigations of tells was by Rosen (1986), which studied tell formation and erosion and identified micro-traces of activities. Geoarchaeological analyses have since been applied to other aspects of tells, including new social and ecological research questions, in a wide range of interdisciplinary archaeological projects, some of which are discussed below.

Concepts and theories

Knowledge of the geoarchaeology of tells is fundamental to interpretation of all archaeological materials within them. Study of mound deposits can inform on the context of all material remains, and geoarchaeology is vital to understanding the significance of those remains, as was stated by Renfrew (1976) with regard to the discipline of geoarchaeology more widely. Interdisciplinary concepts and theories are employed in geoarchaeological analysis and interpretation of tells, as their deposits comprise diverse mineral, bioarchaeological, and micro-artifactual materials, which were selected, deposited, and transformed by a range of natural and anthropogenic agencies and processes. Methods, concepts, and theories to study tells have been drawn from environmental sciences (including soil science, geology, and ecology), material and architectural sciences, and the social sciences (including anthropology and art history). Schiffer (1987) identified a wide range of natural and cultural agents and processes in the formation of the archaeological record. His research remains a fundamental guide to analysis and interpretation of the origin, deposition, and postdepositional alterations of archaeological deposits on many sites, including tells. More recent post-processual approaches consider in greater depth the social and ecological context of archaeological materials and the agency, experiences, and life histories of the individuals and communities that selected and modified the varied materials on sites.

This section discusses concepts and theories in architectural and material culture studies that are vital to geoarchaeological interpretation of the stratified settlement within tells, as mound sediments are principally made up of architectural materials and other human-modified (anthropogenic) deposits. Natural agencies and processes are discussed elsewhere in this encyclopedia. In architectural and artifactual studies, it is widely recognized that materials and artifacts are selected, manufactured, used, and discarded according to a range of ecological, technological, and cultural considerations and that contextual analysis of materials and objects can in turn inform about those very aspects of environment, technology, and socioeconomic roles and relations (Sillar and Tite, 2000; Hicks and Beaudry, 2010). The significance of particular materials can be studied using material culture approaches that examine and compare the general and the specific contexts, properties, and life histories of materials (Robb, 2010).

Regarding the interpretation of microstratigraphic sequences of surfaces and occupation deposits within tells, Kramer (1979) was one of the first to suggest that, even when few artifacts were left on floors (as is the case with many sites), archaeologists could readily identify animal pens, courtyards, kitchens, and living areas by studying the type, thickness, and frequency of surfaces and the accumulated occupation residues, as these clearly varied according to context in her ethnoarchaeological research in Iran. Her observations are supported in principle by Schiffer (1987), who established with the aid of experimental studies with McKellar (1983) that it is the smaller archaeological remains that are more likely to become traces of primary activities, as these are less easily removed by cleaning and survive in thin lenses on floors, while larger artifacts are often removed and curated. As to the value of studying surfaces, architects Leatherbarrow and Mostafavi (2002) argue that the history of particular places and the boundaries between them may be marked by and potentially traceable across surfaces. This is because individuals and communities select specific types of materials for surfaces and arrange and renew these according to the intended use of a place, and surfaces are in turn affected by later activities in that area. These principles and observations have been supported by ethnoarchaeological research in Turkey (Matthews et al., 2000a) and India (Boivin, 2000), where vivid examples have been documented of the use of different surface materials to mark particular events and places in the life history of communities. The anthropologist Bloch (2010) also argues that the study of settings, features, and buildings can inform on continuity and change in social concepts and roles and relations because these material remains, by their durable nature, are used to demarcate particular values, places, and the roles associated with them, which can be repeated and renewed or be contested and changed. Decisions in discard of materials, including residues from activities and building debris, also include consideration of the physical, economic, and cultural value of materials, such that the places in which they were deposited and the specific events, functions, and interpersonal relationships represented may be accessible to the archaeologist through analysis of depositional contexts and traces of the life histories of materials recovered (Hodder, 1987).

In summary, a geoarchaeological analysis of tells has the potential to inform us about the natural and built environment as well as the ecological and cultural strategies and practices of its former occupants by drawing upon interdisciplinary methods and theories, ethnographic comparisons, and experimental approaches.

Ethics

Many tells are excavated and studied by international teams, and it is the ethical responsibility of all concerned to respect local customs, discuss sampling strategies, disseminate results by engaging in public outreach as well as rapid publication, and to acknowledge all assistance. While some geoarchaeological analyses can be conducted in the field, many require transfer or export of samples to scientific laboratories with the permission of relevant authorities in the host country, and the country of destination usually has laws governing the importation of soil and plant materials. It is vital that all analyses be conducted following good laboratory codes of practice and that all field and laboratory samples and records be archived and made accessible for reference when appropriate. Excavation and sampling by their very nature are destructive. Extant section profiles and geoarchaeological samples, therefore, can provide archival records of deposits and features that can be revisited and reexamined as new questions, techniques, and expertise develop, both during the campaign of an excavation itself and in the longer term after the site is no longer accessible. Section profiles and geoarchaeology, therefore, have major roles to play in developing greater transparency and reflexivity in practice (Hodder, 1999).

Interdisciplinary methods in the geoarchaeological analysis of tells

A wide range of geoarchaeological techniques have been applied to the study of tells. The analytical principles and methods of many of these are discussed in other sections of this encyclopedia. This section briefly reviews examples of their application to tells in key case studies and highlights the value of multi-scalar and interdisciplinary research.

Remote sensing is widely applied to identify tells and analyze their geographical distribution and regional context in studies of human-environment relations and settlement and landscape histories (Wilkinson, 2003). The earliest technique employed was aerial photography. Satellite imagery is now applied using high-resolution CORONA and SPOT imagery, the Shuttle Radar Topography Mission (SRTM) digital elevation model, and multispectral analysis using Landsat or Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) data. Where possible, the results are tested and augmented by ground survey and geoarchaeological coring. Examples of integrated remote sensing projects on tells include those in northern and western Syria and northern Iraq (Wilkinson, 2003; Menze and Ur, 2012; Wilkinson et al., 2012), southern Iraq (Pournelle, 2007; Stone, 2013) and new projects in Iraqi Kurdistan (Ur et al., 2013).

Insights into the paleoclimate and environment of tells as well as ecological strategies of the ancient inhabitants and their environmental impact are provided by analysis of sediments, soils, and a range of multi-proxy data from landscape geomorphology, cores extracted from lakes, and cave speleothems (Fortin and Aurenche, 1998; Gasche and Tanret, 1998; Wilkinson, 2003; Djamali et al., 2010; Heyvaert et al., 2010; Deckers, 2011). As one example, the Neolithic mega-site of Çatalhöyük in Turkey was surrounded at least periodically by extensive wetlands when it was occupied, but now it currently lies within a semiarid plain (Boyer et al., 2006) (see entry on "Çatalhöyük").

Geophysical exploration is extensively applied to study the nature and variability of subsurface remains within tells and to provide a guide to excavation and sampling strategies. It has been most effectively employed in investigations of extensive areas of settlement on flatter areas of tells and in multi-proxy programs that use integrated electrical resistivity tomography, magnetometry, and ground-penetrating radar. Particularly successful applications include recovery of the plan of extensive sectors of the 3rd millennium BCE lower town at Tell Chuera, Syria (Meyer, 2007) and elite buildings and administrative areas at Kazane Höyük, Turkey (Creekmore, 2010). Geophysical analyses have also enabled a study of the multilayered structure of tell occupations at the 3rd millennium BCE site of Old Smyrna Höyük in western Turkey (Berge and Drahor, 2011).

Geoarchaeological analysis of active areas of erosion and deposition (colluviation) on tells provides insight into the topography and postdepositional alteration of mounds by prevailing winds and rain, for example (see Rosen, 1986). It can also guide archaeologists to the location of structures and deposits immediately below the tell surface, which together with ground survey of surface finds and features can assist in the choice of excavation areas. By such methods, it was possible to pinpoint hitherto underexplored levels of early 3rd millennium BCE date at the large multi-period site of Tell Brak, Syria (Matthews, 2003a). Surface scraping with a hoe to remove shallow topsoil has proven particularly effective in the ground truthing of geophysical surveys (Matthews, 1996) and in uncovering large sectors of tells that were abandoned at particular time periods and not subsequently occupied. More than one-third of the 3rd millennium BCE urban settlement at Tell Abu Salabikh in southern Iraq has been planned by the use of surface scraping, enabling highly targeted excavations and geoarchaeological analysis of a diverse range of industrial, administrative, and residential areas in studies of the anatomy and socioeconomic structure of a Sumerian city (Matthews and Postgate, 1994).

Opportunities for geoarchaeological analysis of the buildings and stratigraphy within multi-period tells are best provided by a combination of open-area excavation to examine architectural plans over a substantial horizontal tract and step trenches at the edge of a mound or in deep soundings to study settlement and community history

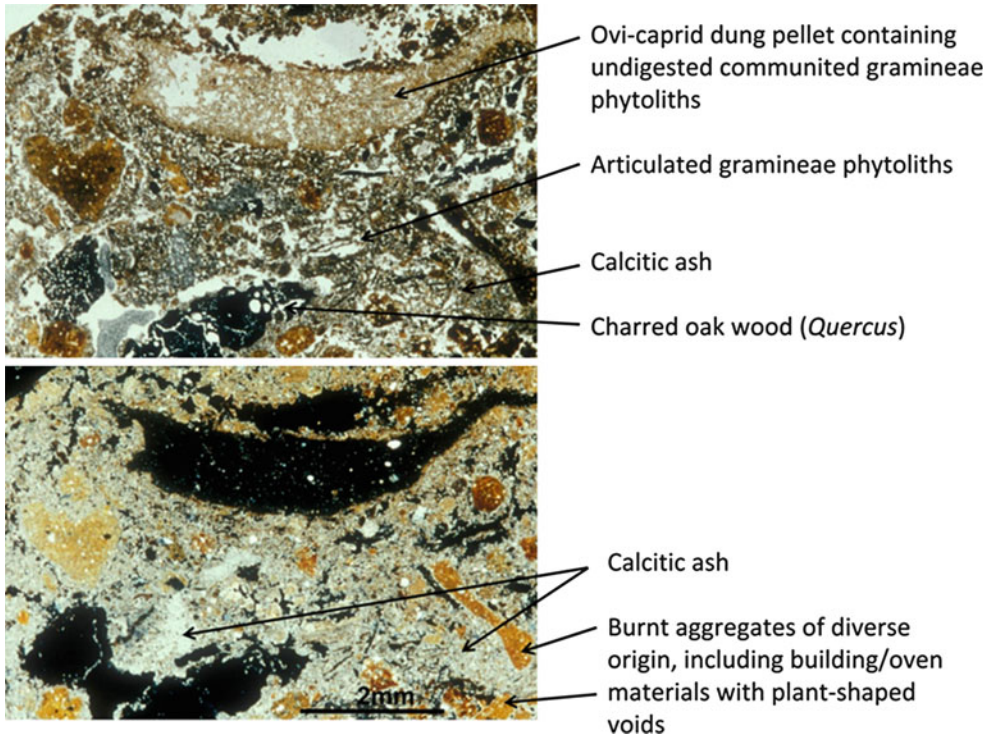
Tells, Figure 3 Multi-scalar approaches linking field and microscopic analyses. Intact block removal from floor deposits and final large resin-impregnated thin section and photomicrograph (Plane-polarized light (PPL)) of fine plastered floors within a Neolithic building, Jani, Iran (Matthews et al., 2013b).

through time. Other opportunities may be provided by analysis and sampling of section profiles through mounds that were cut by river and stream erosion, or road building, as, for example, at the Neolithic site of Jani, Iran (Figure 3; Matthews et al., 2013a). Large section profiles are also available for sampling from older, often large-scale, excavations that can yield significantly enhanced information by the application of new scientific analyses, as at the Neolithic site of Çatalhöyük, Turkey (Matthews et al., 1996). All microscopic or geochemical analyses need to be closely linked to macroscale analysis and recordings of deposits in the field (Courty et al., 1989; McAnanay and Hodder, 2009).

During excavation, it is particularly important that geoarchaeological sampling strategies be discussed with excavators to ensure, first, that samples do not impede nor disrupt excavation aims and objectives and, second, that adequate spot/bulk and intact block samples are collected at key spatial as well as temporal intervals across different rooms, buildings, and areas (Canti, 1995; Farid, 2000; Matthews et al., 2000b). Sampling intervals will vary according to research aims, objectives, analytic and funding resources, as well as macroscopic observations of spatial as well as temporal variations in the character of deposits. Where buildings are small and field analysis of the features and deposits indicates that many different activities were conducted within each space, geoarchaeological sampling intervals may be as frequent as every 0.5–1 m, as has been the case within selected buildings at Çatalhöyük, Turkey (Matthews, 2005a), and Saar, Bahrain (Matthews and French, 2005). Section profiles provide key insights into microstratigraphic histories and may be analyzed at the edge of excavation trenches or gridded squares ca. 1–4 m^2 in size; in half-sections through rooms, areas, or features; or in strategically placed baulks and plinths, ca. 30 cm wide. It is vital that all section profiles be regularly cleaned and examined during excavation and geoarchaeological analysis to enable clear observation of the composition and stratigraphic variation within the deposits as well as the relationships between strata. In order to obtain the sharpest and clearest section profiles, given the complexity and thinness of many deposits on tells, it is recommended that an artist's palette knife be used to cut cleanly through strata and features, followed by removal of dust with a photographer's "rocket" air blower and/or large board for wafting, using a dust mask for health and safety.

Canti (1995: Figure 1) summarizes the strengths and limitations of geoarchaeological analyses that are relevant to tells, as well as differences between micro-contextual analyses of intact block samples (lifted as an undisturbed block) and bulk analyses of loose disaggregated spot samples. With regard to analyses of intact block samples, microscopic analysis of intact depositional sequences in large resin-impregnated thin sections, up to 14 × 7 cm in size, at ×25–400, is proving particularly powerful in analysis of tell deposits (Figure 3), in combination with microanalyses such as scanning electron microscopy coupled with microprobe analyses (e.g., SEM-EDS/X), infrared (IR) and Raman microscopy, synchrotron radiation source micro-IR, micro-X-ray diffraction (XRD), and micro-X-ray fluorescence (XRF) (Courty et al., 1989; Matthews et al., 1997a; Stoops, 2003; Weiner, 2010; Mentzer and Quade, 2013; Anderson et al., 2014). These micro-contextual approaches enable simultaneous high-resolution analysis of diverse mineral, bioarchaeological, and micro-artifactual components and their precise depositional and contextual relationships that are critical to an accurate interpretation of their significance. Many diverse components and depositional lenses are either bulked together or irreversibly separated during standard excavation and sampling procedures. Micro-contextual analyses enable resolution of individual components and depositional units that are not recoverable nor even detectable during routine excavation and sampling, due to their exceedingly fine scale, often <0.1–5.0 mm. Such approaches are thereby providing new high-resolution data on the materials and microstratigraphic histories of tells, examples of which are illustrated in selected case studies below.

One important advantage of micromorphological analyses of tell deposits is that they enable identification of a much wider range of plant types, parts, and materials than other geobotanical or archaeobotanical analyses can accomplish on their own. Most current archaeobotanical

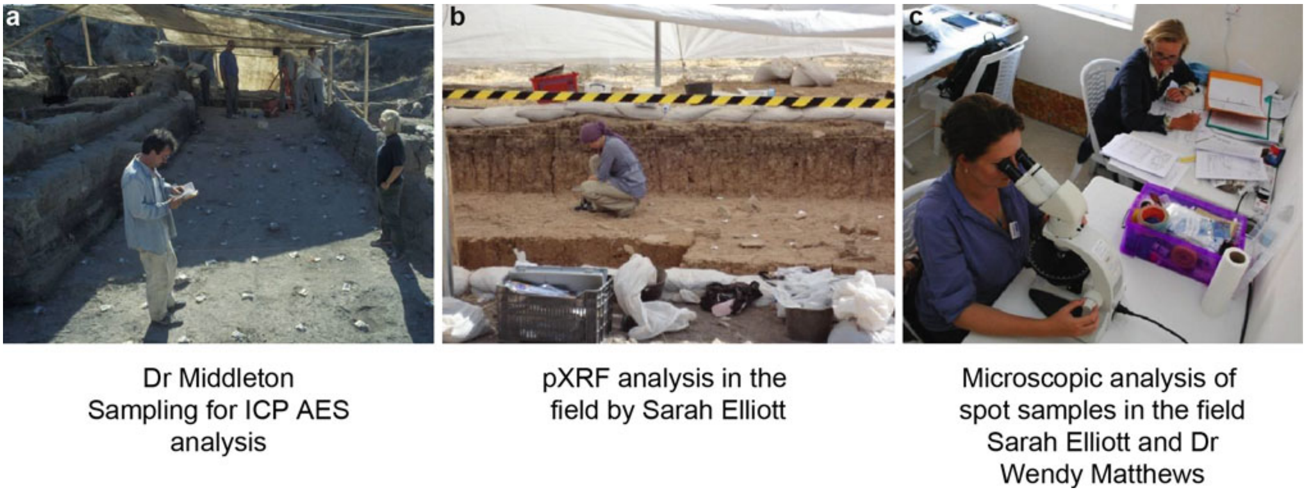


Tells, Figure 4 Diverse plant remains and dung preserved in micromorphological thin sections. Çatalhöyük, fuel in fire-installation, 'Shrine' VIII.25, South Area (PPL (upper); cross-polarized light (XPL) (lower) (Matthews, 2010; Figure 3).

analyses conducted on tells focus largely on charred plant remains recovered by water flotation; this retrieval method yields plants that have been burned at low temperatures, <400 °C. In large resin-impregnated thin sections, it is possible to identify a much broader array of plant materials, including waterlogged or humic plant remains, impressions of plants, silica phytoliths, melted plant silica, calcitic plant ashes, pollen, as well as charred plant remains (Figure 4) (Matthews, 2010; Shillito, 2013). As illustrated in case studies below, plant remains constitute a surprisingly abundant and diverse component of tell deposits, and integrated micro-contextual analyses are providing exciting new insight into the many activities and materials preserved within agricultural and urban sites from as early as ca. 10,000 BCE.

An increasing range of instruments has enabled in situ analysis of tell deposits directly in the field or in field laboratories, providing key data for immediate feedback that can inform ongoing excavation and sampling strategies (Figure 5; Weiner, 2010). One of the more widely used techniques is portable X-ray fluorescence (pXRF) analysis in order to determine the elemental composition of materials (Emery and Morgenstein, 2007) or traces of activities (Frahm and Doonan, 2013; Matthews et al., 2014; Elliott et al., 2015). Spot samples of deposits mounted in clove oil or mineral oil may also be examined using a polarizing light microscope to analyze traces of phytoliths, calcareous dung spherulites, starches, or other mineral and bioarchaeological constituents that can be crucial in identifying specific features such as an early animal pen at Çatalhöyük (Matthews, 2005a) and to inform subsequent sampling. Other field techniques include terahertz imaging to study subsurface layers, such as paintings situated below layers of plaster also at Çatalhöyük (Walker et al., 2013).

Many geoarchaeological analyses are applied to spot and bulk samples in specialist laboratories to characterize the origin, deposition, and postdepositional alteration of materials and deposits recovered from tells. Under controlled conditions in the laboratory, individual components and layers in block samples may be subsampled prior to resin impregnation in order to provide even greater precision in correlating results from spot/bulk samples with high-resolution micromorphological analyses in thin section (Shillito and Matthews, 2013). Elemental analysis by XRF or inductively coupled plasma mass spectrometry (ICP-MS) is used to characterize source materials for provenance studies and to determine the presence of elemental enhancement or depletion in tell deposits by comparing results with those of natural, ethnographic, or experimental materials – see the studies by Middleton et al. (2005) and Davidson et al. (2010) below. Other analyses include particle size to study sources of architectural and natural materials (Davidson and Shackley, 1976) and gas chromatography-mass spectrometry (GC-MS) to identify biomarkers of human and animal feces and lipids



Tells, Figure 5 Geoarchaeological sampling and analyses in the field; (**a**) William Middleton sampling for ICP-AES analysis; (**b**) pXRF analysis in the field conducted by Sarah Elliott; (**c**) microscopic analysis of spot samples in field laboratory by Sarah Elliot and Wendy Matthews.

within settlements and their ecological, dietary, and social significance (Bull et al., 2005; Shillito et al., 2011). Bioarchaeological analyses include study of spot samples of plant silica phytoliths and ashes (Rosen, 1992; Albert et al., 2008; Shillito, 2013). Analyses of residues from combined wet screening and flotation provide a larger comparative sample size of selected microarchaeological remains for study of activity areas (Rainville, 2005; Saeedi, 2010; Parker and Foster, 2012).

Interpretation of results from these analyses requires access to archives and atlases of key reference materials and comparanda to identify components and evaluate similarities and differences. Analyses of local and more distant sediments and geologic samples are conducted to characterize potential source materials and environments. Ethnoarchaeological and experimental studies have aided geoarchaeological investigations of tells. These have included analyses of the composition, technology, frequency, and significance of plastering (Boivin, 2000; Matthews et al., 2000a) and analyses of the origin, morphology, and taphonomy of deposit constituents such as phytoliths (Tsartsidou et al., 2008, 2009), ash (Shahack-Gross and Ayalon, 2013), and animal dung (Shahack-Gross, 2011; Elliott et al., 2015). To examine patterning in the types of materials, surfaces, and residues on tells, many researchers have identified and classified deposits according to key types (facies) and properties (Matthews et al., 1997a; Maghsoudi et al., 2014).

Robust dating programs and modeling are required to evaluate the time intervals represented by specific depositional units and sequences on tells. An intensive high-resolution ^{14}C dating program and Bayesian model is currently being constructed to date the history of buildings and key societal changes at the mega-site of Çatalhöyük, 7100–6000 BCE (Bayliss and Farid, 2012). Estimates of the timescales represented by individual strata and sequences can be calculated by counting the number of layers within well-dated stratigraphic horizons, as at Çatalhöyük (Matthews, 2005b). Although this approach can suggest that the duration of each unit was the same, it follows routine procedures in the environmental sciences, such as the counting of lake varves, for example, and minimally, it provides an estimate of the order of time represented by a sequence. There could be greater application of age-depth models to tells, building on Davidson et al. (2010).

In summary, tells comprise highly complex materials and microstratigraphic sequences formed by diverse agencies and processes, and thus they require interdisciplinary analytical strategies to understand the rich cultural and environmental remains and continuity and change in human occupation at these repeatedly occupied sites. An effective way to study the geoarchaeology of tell sites is to apply a - multi-scalar approach that links field observations and records of section profiles, plans, and sample locations with geomorphological, geophysical, microarchaeological, micromorphological, bioarchaeological, geochemical, and mineralogical analyses.

Geoarchaeological analyses of tells in practice: selected case studies

The following sections review selected case studies to illustrate the range of geoarchaeological analyses conducted on tells. They reveal the characteristics and significance of specific components, materials, features, and contexts at particular sites, and they show how analyses can inform on key research questions in the study of site histories and ecological and social strategies. The discussion begins with examination of architectural materials, occupation deposits, and commonly occurring features and contexts that include fire installations, animal pens, and burials. It then considers the histories of buildings and their destruction, and industrial areas, open areas, and middens. It concludes with a consideration of natural agencies and postdepositional alterations that affect tell deposits.

Architectural materials: mudbricks, mortars, and plasters

A considerable proportion of ancient settlement mounds comprise either in situ architectural materials in walls and buildings or the leveled or collapsed debris from these former structures. Geoarchaeological analyses have been applied to investigate the source, technology, and social significance of architectural materials and the structures in which they were used. Many architectural materials can be identified by their context, form, and composition. Many mudbricks and plasters contain reworked and often homogenized natural or anthropogenic sediments, or a mixture of both, often with traces of vegetal and mineral temper to provide tensile strength and flexibility. For an introduction to modern earthen materials and construction, see Houben and Guillaud (1989).

Mudbricks

Many walls built on tells were constructed from rammed earth or shaped mudbricks and mortar, even where stone was available. Mudbricks at the Neolithic mega-site of Çatalhöyük have been examined using micromorphology, XRD, XRF, particle size, loss on ignition, and magnetic susceptibility, and the results have been compared to analyses of locally available materials. Studies by Tung (2005) and Love (2012) established that there was significant variation in the materials and methods of manufacture between different buildings, suggesting that choice of materials and building traditions were organized at the scale of individual households. Unworked aggregates of original source materials indicate that many of the later mudbricks on the site were manufactured from alluvial deposits (Matthews et al., 1996).

At tells dating to later periods, geoarchaeological analyses have been applied to examine whether architectural materials and structures were the product of large-scale projects and organized labor. At the Egyptian site of El Hibeh, 1064–664 BCE, portable X-ray fluorescence (pXRF) analysis established that the necropolis walls were built from two local sources of sediment by organized groups of laborers working systematically from two opposing corners of the building, providing the first evidence of organized work parties in construction of mudbrick structures in Egypt (Emery and Morgenstein, 2007). Microscopic, mineralogical, and chemical analyses – XRD, XRF, and neutron activation (NAA) – of mudbricks from three Bronze Age sites in East Crete by Nodarou et al. (2008) indicate that although locally available materials were used, there was some cross-community standardization in the manufacturing process. Analysis of Roman and Islamic bricks from Thamusida, Morocco, by Gliozzo et al. (2011) has highlighted more complex production and distribution of architectural materials, with some evidence for importation of bricks in the first century AD, perhaps linked to wider trade networks and use of bricks as ballast.

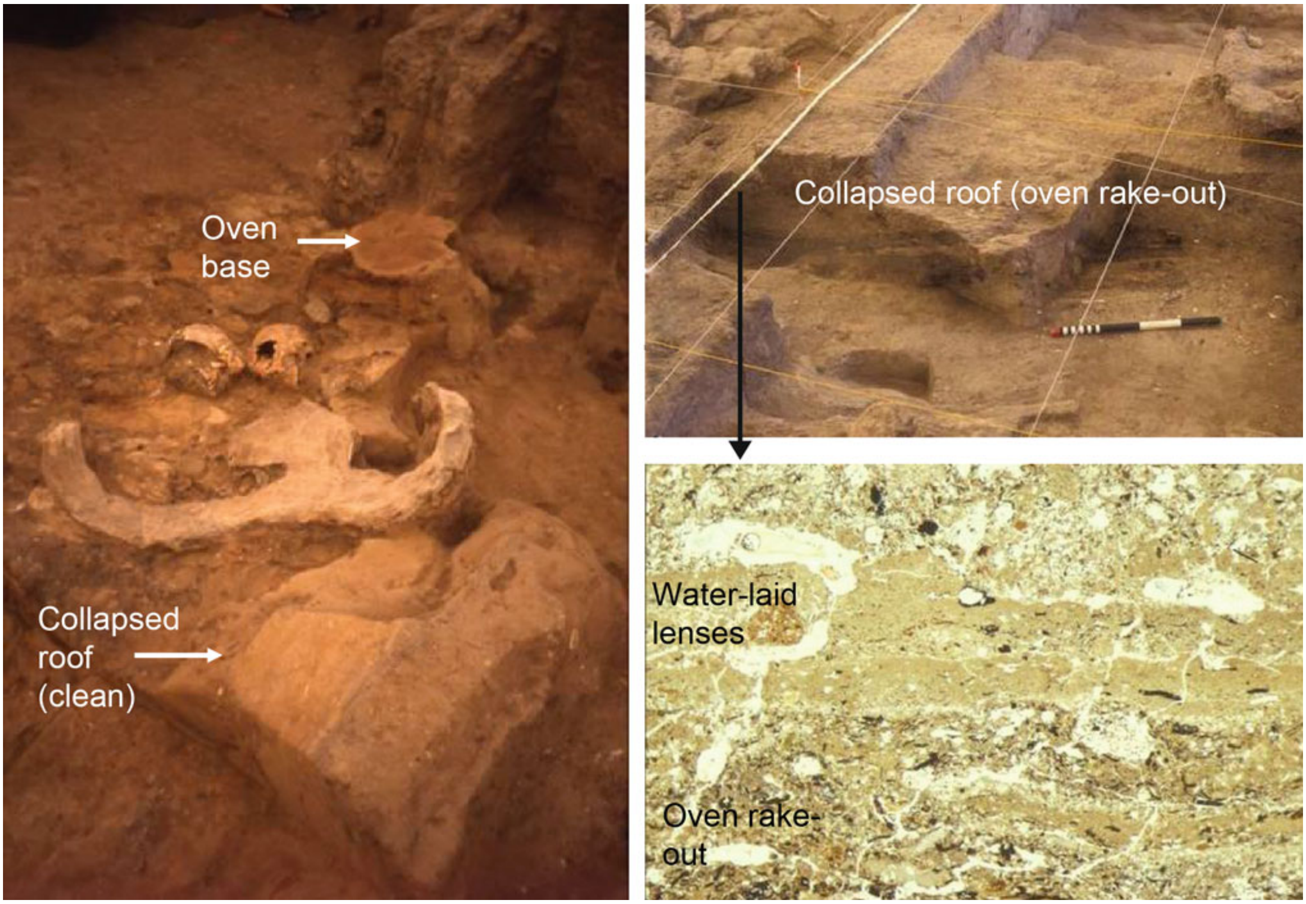
Roofing

Remains of roofing appear to be remarkably rare on tells. They appear mostly to have been reworked during leveling and infilling of buildings. Some of the earliest known roofing that is likely to have afforded year-round and not just seasonal occupation, marking a major transition toward sedentism, has been identified at Tell Qarassa, Syria, by micromorphological, phytolith, and wood charcoal analyses (Balbo et al., 2012). This durable roof was constructed from substantial radial timbers and sedges covered by a layer of grasses and then a thick daub coating with plant temper that would have reduced shrink-swell during wetting and drying and lightened the weight load.

Large, rare slabs of collapsed flat roofing, up to ca. 1 m in length from the later Neolithic of Çatalhöyük, have been analyzed using micromorphology, and the results have identified remarkable spatial and seasonal variation in rooftop activities by study of the multiple sequences of surfaces and occupation in these roof slabs (Figure 6; Matthews, 2012). This research established the presence of a roofed upper story room, as well as an open area on the roof that was used, among other activities, for seasonal cooking probably in warmer drier months, as the fuel rake-out next to an oven was periodically covered by lenses of undisturbed rainwash sediment and crusts that probably accumulated in the winter when the oven was not used. These results highlight the range of activities for which evidence is usually missing in analyses of ground floor plans alone, and they clearly demonstrate the importance of roofs in social interaction as well as food production and processing.

Plasters

The production of fired lime plaster represents one of the earliest manufactured construction materials, used from at least 12,000 BCE to pave surfaces within cave sites and in early Neolithic sites to pave floors and model plaster skulls (Kingery et al., 1988). Distinction between fired and non-fired lime plasters using optical microscopy, SEM EDX, and XRF, however, remains problematic, as both materials have the same mineralogical composition. Regev et al. (2010a, 2010b) have developed an integrated method for distinguishing between non-fired and fired lime and for identifying hydraulic lime. They used FTIR (Fourier transform infrared) spectroscopy and IR microscopy to identify structural changes in minerals affected by heat from firing, in conjunction with acid dissolution, XRF, XRD, micromorphology, and SEM-EDS, at the Iron Age site of Tell es-Safi. Mentzer and Quade (2012) have applied integrated micromorphological, compositional analysis of major and minor trace elements using micro-XRF and oxygen (δ^{18}O) and carbon (δ^{13}C) stable isotopic



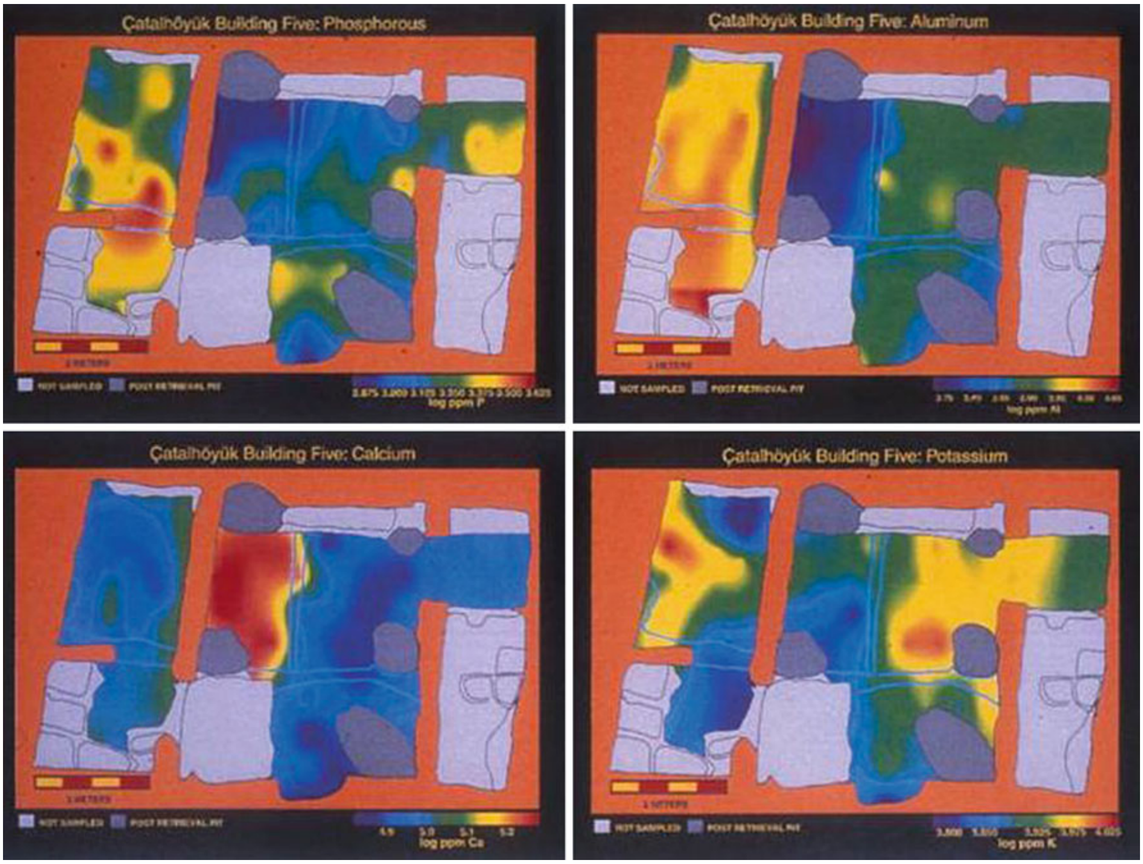
Tells, Figure 6 Collapsed roof: Cycles of oven rake-out and water-laid deposits from periodic cooking on the roof, Building 3, Çatalhöyük, Turkey, ca. 6500 BCE (PPL) (Matthews, 2012).

analyses to distinguish between calcareous ash and lime plasters at the early Neolithic site of Aşıklı Höyük in Turkey. Micromorphology, microanalysis, and 3D mapping of multiple layers of wall plasters and pigment at the Neolithic site of Çatalhöyük are enabling identification of the specific materials that were selected for surface materials and paintings and their probable symbolic significance (Matthews, 2005a; Matthews, 2005b; Matthews et al., 2013b; Anderson et al., 2014). Field and micromorphological analyses of the arrangement and frequency of plasters at a number of sites suggest that these surface materials were used to define particular activity areas and to mark specific events. The evidence for this is discussed below in the section on life histories of buildings in conjunction with consideration of spatial and temporal variation in occupation deposits.

Occupation deposits

As on other types of archaeological site, accumulated occupation deposits from activities on tells comprise diverse materials introduced by many natural and anthropogenic agencies and processes (Schiffer, 1987). As many, but not all, tells are located in semiarid regions, the materials preserved are generally only those that can survive in an oxidizing environment. Some of the most commonly occurring non-burned and burned materials in geoarchaeological samples include rock fragments, minerals, and sediments; aggregates from natural and anthropogenic materials and deposits; fragments of architectural materials or micro-artifacts such as ceramics and lithic debitage; diverse plant species, parts, and materials; food remains; coprolites from humans and animals; other bioarchaeological remains including fragments of animal bone (including fish and bird), mollusks, and microfossils; and a range of postdepositional materials and features discussed below. The associations of these materials with specific activities are discussed in the following sections.

Multielement analyses have been used to characterize occupation deposits on tells with the aim of identifying specific groups of elements that can be linked to particular activities, as at the Neolithic site of Çatalhöyük, Turkey, by ICP-AES (inductively coupled plasma atomic absorption spectrometry) (Figure 7; Middleton et al., 2005). ICP-AES analyses at the Late Bronze Age and Early



Tells, Figure 7 Elemental analysis of floors and activity areas, Building 5, Çatalhöyük (Middleton et al., 2005; Figures 20.1–4).

Iron Age tell of Zenobia in Greece by Davidson et al. (2010) established that contexts were most clearly differentiated on the basis of their phosphorus (P) and chromium (Cr) content, and that elemental loads were highest in occupation deposits overlying floors and in pit fills, and that they were lower for roads, alleys, and yard contexts. At the Classical-Hellenistic site of Düzen Tepe, Turkey, ICP-OES (inductively coupled plasma optical emission spectroscopy) analyses by Vyncke et al. (2011) enabled the identification of cooking and hearth areas, a latrine, and an area of high traffic, for example. Given the diversity of materials and depositional pathways on tells, however, no widely applicable diagnostic criteria have been established. Local variability in elemental composition and sources of materials must be evaluated and further experimental, ethnographic, and geoarchaeological analyses conducted at a range of site types to establish more fully the significance of elemental variation in occupation deposits (Wilson et al., 2009).

Fire installations

Fire is used in many activities on tells, including for daily food processing and cooking, heating and warmth, production of architectural materials such as fired lime or baked bricks and tiles, manufacture of artifacts such as pottery and metal objects, as well as ritual practices. Geoarchaeological analyses have been conducted to investigate (1) sources of fuel and their environmental and ecological implications; (2) use of specific fire installations by studying fuel type, burning temperatures, and residues in and around hearths; and (3) technologies and scales of production, with reference to ethnoarchaeological and experimental studies.

Mentzer (2014) provides a particularly comprehensive review of the wide range of analytical techniques that have been applied to the study of combustion features and the residues from these. Her research shows that, to date, more geoarchaeological studies have been conducted to investigate Paleolithic fire installations than those of later periods, partly because combustion features were a principal focus of activities within cave sites in particular, and they are often among the better preserved features. She provides some examples of burned plant remains from the early Neolithic site of Aşıklı Höyük, Turkey, and explores the characteristics of calcitic ashes further in Mentzer and Quade (2012).

Later Bronze Age and Iron Age fire installations in the Levant have recently been systematically analyzed by

Gur-Arieh et al. (2014) using a range of analyses building upon studies by Berna et al. (2007) and Weiner (2010). In their integrated study, micromorphological analysis was used to identify fuel types and its depositional context and sequence of burning in conjunction with analyses of spot samples of phytoliths and dung spherulites. The principal fuel identified across all sites was wood mixed with some dung, suggesting that this was the preferred source of combustible material across different environments and cultural groups in the Levant. FTIR spectroscopy established that temperatures up to 900 °C could be reached using this mixed fuel in these early urban mud-constructed installations.

Greater variation in the selection of fuel, however, has been identified by micromorphological analysis of the diverse plant remains from a range of hearths and ovens sampled along a geobotanical transect through other regions of the Middle East, with some evidence of variation in selection or access to fuel in different regions as well as by different households and during the life cycle of individual households (Matthews, 2010). Generally, in more temperate steppe-forest regions, wood was used as a significant source of fuel, in conjunction with reeds, grasses, and animal dung, as at the Neolithic site of Çatalhöyük in Turkey (Figure 4). In the more steppic regions of northern Syria and southern Iraq, where there were few trees, there was much greater use of reeds, grasses, and animal dung as fuel, preserved predominantly as phytoliths and calcitic ash, as at the 3rd millennium BCE early urban sites of Tell Brak and Abu Salabikh. On the steppic and desertic island of Bahrain with coastal mangroves, date palm leaflets were widely used as fuel, preserved predominantly as silica phytoliths, which are rarely recoverable by flotation as they burn leaving little residual carbon (Nesbitt, 1993). Integrated geoarchaeological and archaeobotanical analyses, therefore, are making a significant contribution to our knowledge of early agricultural and urban ecology and fuel and plant use at tells across the ancient world.

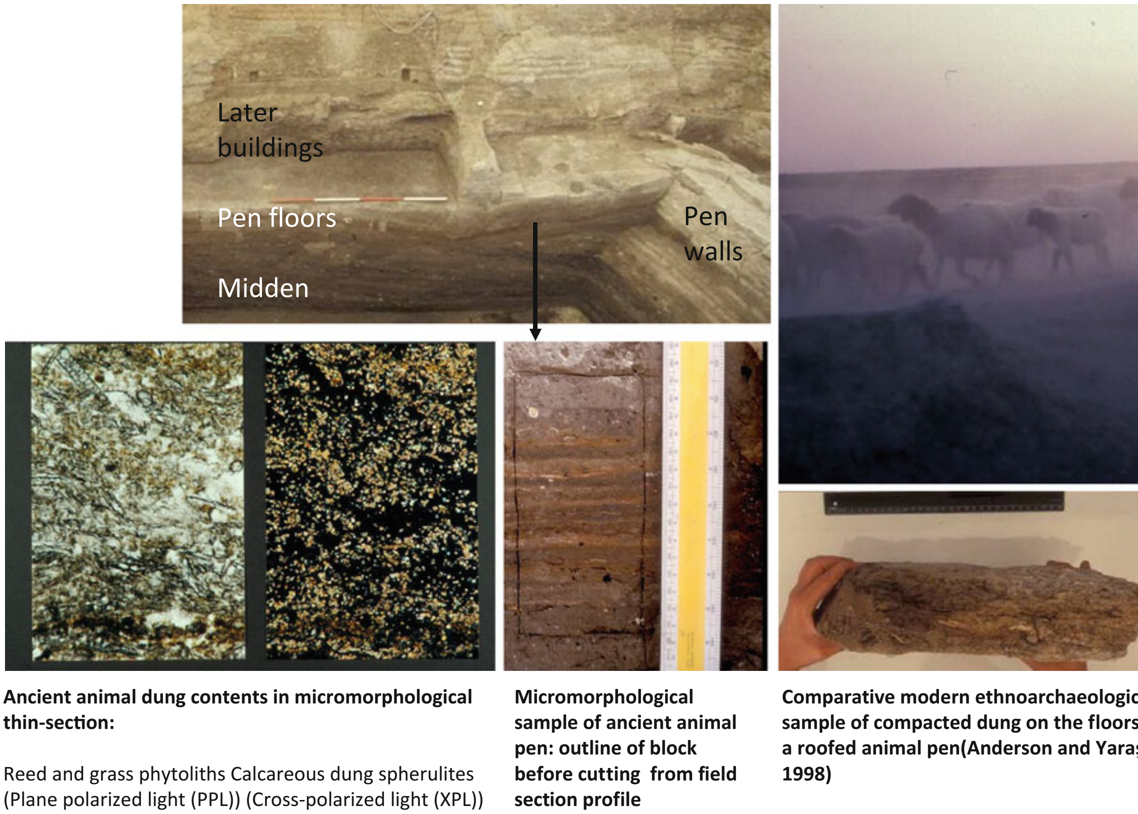
Animal dung and penning

Animal dung is difficult to identify in the field and in bulk archaeobotanical assemblages of charred remains. Dung often fragments during combustion, and its plant contents are released, making it difficult to establish whether the plant residues recovered from tells derive from animal or human consumption, or other human activities (Miller, 1996). Animal dung, however, can be securely identified by micromorphological analysis of dung form, contents, and calcareous spherulites that form in the guts of animals during digestion (Courty et al., 1989; Brochier et al., 1992; Canti, 1999) and by GC-MS identification of coprostanols and bile acids that are species specific (Bull et al., 2005). On tells, these analyses have been complemented by (1) portable XRF analysis of excavated surfaces to detect elevated levels of phosphate in the field, which may indicate the presence of dung residues and can thus serve as a guide to where to sample for better preserved dung, and (2) integrated phytolith analysis to study animal diet, ecology, and seasonality (Figure 8; Albert et al., 2008; Matthews et al., 2013b, 2014; Portillo et al., 2014). As outlined in the methods section above, animal dung can also be readily identified in the field by microscopic analysis of spot samples of deposits, as it is recognizable by the presence of dung spherulites; excavation and other sampling strategies can then be adjusted accordingly, as at Çatalhöyük, Turkey (Figure 5; Matthews, 2005a).

Application of these integrated geoarchaeological analyses to identify animal dung is contributing significantly to our understanding of the origins of agriculture in the Middle East, which is one of the heartlands of the world where many of the animals that we rely on today (goat, sheep, pig, cattle, and dog) were first domesticated. The earliest traces of domestication cannot be recognized by the study of animal bone morphology alone, as changes in species size may not be detectable for more than 1,000 years after domestication (Zeder, 2009). Zooarchaeological research has relied instead upon the detection of changes in kill-off patterns to identify evidence of management strategies. More recently, however, close proximity of animals to sites as well as management of animals by humans has been securely established by identifying the presence of animal dung at several Neolithic tells using integrated geoarchaeological analyses (Figure 8; Matthews, 2005a; Matthews et al., 2013a; Matthews et al., 2013b; Stiner et al., 2014). The identification of animal dung in pens, in open areas, and as a major source of fuel is revolutionizing our knowledge of human-animal interrelations and ecology at the origins of agriculture and early settled life as well as during the later development of cities and early states (Matthews and Postgate, 1994; Matthews et al., 2001; Shahack-Gross, 2011).

Burials

The InterArchive project (InterArchive, 2012) is currently investigating new high-resolution traces of human burial practices and rites by integrated micromorphology, geochemistry, and mineralogical analyses, and this research includes study of tells such as Çatalhöyük. Previously, geoarchaeological analyses of burials on tells have been limited. One exception is the large interdisciplinary investigation of a royal tomb complex at Qatna, Syria (Pfälzner et al., 2013). Another relevant case study is Karkanas et al.'s (2012) investigation of mortuary practices through the study of tomb preparation, burial and memorial rites, and reuse, as depositional acts and events in an integrated field and micromorphological study of the multiuse of Mycenaean chamber tombs at Ayia Sotira, Greece. They established that the floor of the tomb was plastered during construction and reuse and that the tomb was not left open for long between uses as there was little sediment accumulation on the floors. They were also able to identify sequences of backfilling and reopening by studying



Tells, Figure 8 Animal dung in a pen and traces of early animal management at Çatalhöyük, ca. 7000 BCE (Levels XII–XI and VIII) (After Matthews 2005a, Figures 19.25 and 19.26; Matthews et al., 1996, Figures 15.19 and 15.20). *Lower left*: Ancient animal dung contents in micromorphological thin section; reed and grass phytoliths (PPL) and calcareous dung spherulites (XPL). *Lower middle*: Micromorphological sample of an ancient animal pen; outline of the sediment block before cutting it from the field section profile. *Lower right*: Comparative modern ethnoarchaeological sample of compacted dung on the floor of a roofed animal pen; see also Anderson and Ertuğ-Yaraş (1998).

deposit particle size, bedding, and erosional surfaces, providing a framework for understanding the complex sequences of mortuary rites and their wider social significance.

Houses and life histories

One of the first comparative geoarchaeological studies of buildings on tells was conducted at four early urban settlements across the Middle East to investigate the potential of microstratigraphic and micromorphological analyses and to identify and compare traces of activities in different environmental and sociocultural contexts (Matthews and Postgate, 1994; Matthews et al., 1997a). This research was conducted in consultation with Dr Marie-Agnès Courty and Dr Richard Macphail and in collaboration with plant anatomists from Kew to help with identification of the diverse plant remains in thin section, which are one of the most abundant residues of ancient activities on tells. These studies reinforced the value of the new microstratigraphic and micromorphological approaches in analyzing the complex genesis of archaeological deposits through simultaneous study of the diverse components of site earth in their precise depositional context at a resolution not possible with routine excavation and sampling (Courty et al., 1989). They also demonstrated the potential for integrating micromorphological analyses with analysis of microarchaeological residues from wet sieving and flotation, which is widely applied in studies of households (Rainville, 2005; Saeedi, 2010; Parker and Foster, 2012).

These analyses established new diagnostic criteria for identifying specific types of activities on tells and within buildings according to (1) the type, thickness, and frequency of surfaces and (2) the impact of activities on them as well as the residues left on them as determined in the field and later at higher resolution in thin section (Matthews and Postgate, 1994; Matthews et al., 1997a: Table 2, Figure 3). Irrespective of variation in local resources and the scale of cultural complexity and technology, general trends were identified in the selection, placement, and frequency of surfaces for particular areas, and regularities were observed in the types and abundance of residues that accumulated within these areas. Such patterns were suggested in ethnoarchaeological research by Kramer (1979) and by Schiffer (1987) and supported by subsequent theory and research in architecture (Leatherbarrow and Mostafavi, 2002) and archaeology (Bloch, 2010; Robb, 2010), as discussed above. In addition, these microstratigraphic and micromorphological analyses enabled the study of specific and contingent histories of particular buildings and communities on tells at unprecedented temporal resolution by analyzing previously unresolvable single depositional units that were <0.012–5 mm thick and representative of specific events on the order of monthly-seasonal and longer timescales.

In summary, key characteristics and emergent criteria in the identification of specific types of activities and areas include the accumulation of (1) multiple layers of fine plaster, often with traces of mats/coverings, and few occupation residues in reception/sitting rooms or areas; (2) thick layers of packing resistant to insects and rodents and either residues of stored items or scoured surfaces following removal of these in food storage areas; (3) some or rare medium-coarse plasters and periodic fuel rake-outs and occasional sweepings in food preparation and cooking areas; (4) either paved or unpaved surfaces depending on sociocultural context, occasional traces of wind or water-laid deposits, and diverse residues from specific activities in courtyards; (5) reworked and fragmented surfaces and deposits in trampled areas within entrances and rooms of courtyards; and (6) selection of often rare or exotic materials to mark the place or event, including exceptional plaster sources or washes of pigments (often red) or scattering of pigments and specific materials, in ritual areas or in association with events relating to ritual. What tends to vary within each area, building, and community are the source and type of materials, and the articulation, organization, and scale of construction and events, according to environmental and sociocultural context.

The following section briefly summarizes selected specific observations on the particular histories of buildings at each of the four tells and their wider significance. At the Neolithic mega-site of Çatalhöyük, it was established that while many buildings had ritual features such as wall paintings, sculptures of animal heads, and subfloor burials, these buildings were not "shrines" but also housed a full range of residential activities, highlighting and documenting the proximity and history of "domestic" and "ritual" practices (Matthews, 2005b; Hodder, 2010; Matthews et al., 2013b). The repetition of similar patterns across different houses, and through many phases of the sites, suggests considerable conformity, predictability, and continuity in social roles and relations that are likely to have been important factors in the longevity of occupation at this large ca. 13 ha and 20 m high tell. The end life of the buildings, however, was more varied and contingent, ranging from dismantlement and immediate rebuilding suggesting continuity to destruction by fire or use as a human latrine (confirmed by GC-MS) and midden suggesting social discontinuity (Matthews, 2005a). New studies are examining the resource management, use, and ecology of individual houses at this and adjacent sites (García-Suárez, 2014), as well as other Neolithic sites in the Central Zagros (Matthews et al., 2013).

At the ca. 2500 BCE Sumerian city of Abu Salabikh in southern Iraq, there was greater differentiation in building size and number of rooms. Even the smallest buildings, however, had at least one larger well-plastered and clean reception room, highlighting the importance of this social space, in addition to areas for storage, food preparation, cooking, ritual, as well as courtyards and latrines (Matthews and Postgate, 1994). By contrast, many buildings at Tell Brak were monumental in scale (discussed below). At the trading settlement of Saar, Bahrain, ca. 1800 BCE, excavation and sampling in 1 m^2 grid squares revealed remarkably clear separation yet close proximity of a wide range of household activities within the small two-to-three roomed buildings; repetition of this pattern within houses and across houses suggested remarkable community cohesion and consistency in social roles and relations (Matthews et al., 1997a; Matthews and French, 2005). When the copper trade started to shift to sources in other regions, many of these buildings were abandoned and infilled with windblown sand.

In other studies, Portillo et al. (2014) investigated the range and organization of activity areas within buildings to obtain information about spatial and diachronic patterns in household strategies at the Neolithic site of Tell Seker al-Aheimar, Syria, late 8th to early 7th millennium BCE, by analysis of microstratigraphic field observations, and phytoliths and dung spherulites from spot samples in conjunction with ethnoarchaeological research. This research identified areas for storage, cereal processing (wheat and barley), cooking areas where dung fuel was used, and clean well-maintained spaces within large multiroomed rectangular buildings; these deposits contrasted with accumulations of refuse in the open areas, thus highlighting the distinction made in the Neolithic between interior and exterior spaces.

Maghsoudi et al. (2014) have identified and characterized many activity areas at three sites in the Qazvin plain, Iran, between 5350 and 450 cal BCE, and at least nine major deposit types (facies) relating to house construction, food preparation and consumption, combustion features and fuel, waste disposal, and colluvial and alluvial processes. The results are being incorporated into an interpretation of long-term continuity and change in socioeconomic developments from the late Neolithic to the Iron Age that included agricultural intensification and increasing social complexity, long-distance trade, and craft specialization.

One of the aims of geoarchaeological research currently being conducted on tells in Greece is to distinguish between site formation processes on tells and those affecting coeval flat extended sites, which are argued to represent different forms of settlement and socioeconomic strategies from the Neolithic onward. An extensive geoarchaeological study by Karkanas and Van de Moortel (2014) at the Bronze-Iron Age tell of Mitrou (2400–900

BCE) has established that the earliest buildings were repeatedly resurfaced with diverse materials. At the start of the Late Bronze Age, however (ca. 1700/1600 to the early fourteenth century BCE), buildings were less frequently plastered, suggesting less continuity and emphasis on individual houses/domestic units as social arenas, coinciding with the construction of new elite centers.

Monumental buildings

Monumental buildings were constructed on many tells as a focus for particular groups and events from the earliest stages in sedentary life, >9600 BCE. Geoarchaeological analyses have been conducted to study the materials and history of these buildings to discover how they and the people and events associated with them were differentiated from those of other buildings (Matthews et al., 1997b; Shahack-Gross et al., 2005). As one example, the regional center of Tell Brak, Syria, was a particular focus for monumental building (Oates et al., 2001). Micromorphological analyses of the two major building complexes in the mid- to late 3rd millennium BCE, Areas SS and FS, have highlighted how the floors and walls of many rooms and courtyards were differentiated from other buildings by the extensive use of resources such as thick mudbrick walls and foundations, multiple layers of plaster, and use of a composite white plaster manufactured from fired gypsum and fired lime not identified elsewhere. These buildings and their courtyards were also regularly maintained in contrast to more public spaces in adjacent open areas that had rough surfaces and dung accumulations (Figure 9; Matthews, 2003).

Destruction and abandonment

Geoarchaeological analyses are making a major contribution to our knowledge of the history of the destruction and abandonment of buildings and settlements on tells by enabling high-resolution stratigraphic analysis of the sequence of both natural and anthropogenic events. Integrated field and micromorphological analyses of two monumental building complexes at Tell Brak have established that the Area SS complex was deliberately infilled to a depth of up to 5 m, as there are clear tip lines and sorting from rapid infill, and Area FS was burned following a period of looting and the walls then pushed in (Matthews et al., 2001; Oates et al., 2001). Approximately coeval with this destruction, another area of the mound, Area HS3, was abandoned and the walls left to collapse and the street to infill with windblown sediment and building debris, as also shown by integrated analyses. Prior to this abandonment, a hoard of gold and silver items had been rapidly buried beneath a floor and was never retrieved. Other approximately coeval episodes of abandonment have been identified by archaeological and geoarchaeological analyses at sites across northern Syria; their link with possible climatic stress and social unrest is widely debated and dependent on ongoing research and dating of these events (Dalfes et al., 1997; DeMenocal, 2001; Weiss et al., 2012).

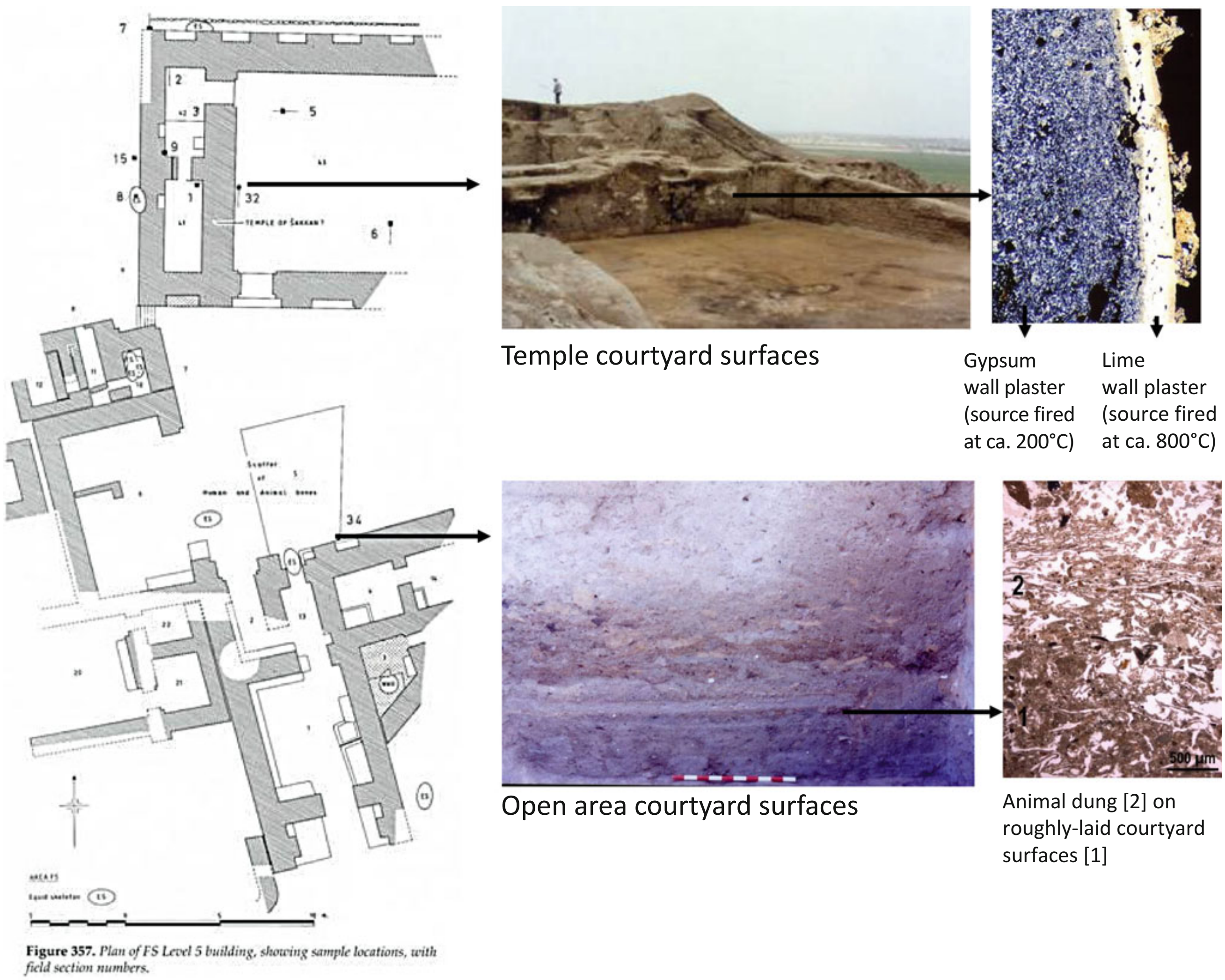
A major destruction layer at Tell es-Safi/Gath, Israel, in the mid-/late ninth century BCE, was investigated by integrated field observations and infrared spectroscopy, phytolith, and ceramic organic residue analysis (Namdar et al., 2011). Analysis of the 80 cm thick destruction horizon indicated several destruction stages spanning decades with different destruction and depositional pathways for specific parts of structures. Some areas were burned, including roof sections; others collapsed or were left standing and eroded over time, providing important insight into the context of the associated artifacts and human residues and of social change.

For buildings that were not destroyed, ethnoarchaeological research has shown that there may be a devolution in use of spaces from living to use for storage and then finally as latrine or refuse areas (David and Kramer, 2001). A similar devolutionary sequence has been identified in an Early Iron Age Phoenician monumental building at Tel Dor by Shahack-Gross et al. (2005). Micromorphological, FTIR, and phytolith analyses suggest that the remains on the well-prepared fired lime floor of the building may not relate to the major period of its administrative or ceremonial use but to the period following this. The floor is covered by a thin layer of sand and clay perhaps from abandonment, followed by evidence of fish processing and eventually ending with animal penning, providing important insight into primary and secondary uses of buildings throughout their life histories. Longer-term processes in the abandonment of tells, processes of erosion, and the formation of topsoil are characterized by Davidson et al. (2010: Figure 3) at Xeropolis, Greece, after its abandonment in the Early Iron Age.

Industrial areas

As major centers of population, tells were often loci for the production of goods and services, and the sedimentary sequences associated with these can provide an important record of these industries. The principal aims in geoarchaeological analyses of the industrial areas of tells are to identify the sources of materials and the nature, scale, and stages of production, as well as to characterize the technological skills required and the socioeconomic context of the industries, whether they were conducted within domestic or larger units. Schiffer (1987) notes that industries producing considerable debris as well as noxious or hazardous by-products, including smoke, may be located at the edge of settlements, and that debris may accumulate and be redistributed within the vicinity of the industrial area due to principles of least effort.

As one example of early industry, micromorphological analysis of production areas for fired lime to be used as plaster in the early levels of Çatalhöyük has established that dung, not wood, was the principal source of fuel and that local marl was the principal source of carbonate (Matthews, 2005a). Analysis of the small size and



Tells, Figure 9 Monumental building sequences and surfaces, Area FS at Tell Brak, northeastern Syria (After Matthews et al., 2001; Figures 357 and 363). *Upper* images: Temple courtyard surfaces showing gypsum wall plaster (source fired at ca. 200 °C) covered by thin white layer of lime wall plaster (source fired at ca. 800 °C). *Lower images*: Open-area courtyard surfaces in section showing in microscopic view animal dung (2) on roughly laid courtyard surface (1).

periodicity of these areas suggests that production was small scale at the household/neighborhood level (Cessford, 2007).

Larger-scale production has been investigated at several later tells occupied in the Bronze Age. At the Sumerian city of Abu Salabikh in Iraq, ca. 2500 BCE, micromorphological analysis of an extensive pottery production area at the northern edge of the settlement established that this prolific kiln-based industry was sustained by using dung as the major source of fuel and that high-firing temperatures were achieved, as some dung is preserved as partially melted silica (>850 °C) and calcitic ashes in the highly fired debris with pottery slag surrounding the kilns (Matthews and Postgate, 1994). Dung is still a preferred source of fuel for some traditional potters, as it burns more consistently than many woods (Sillar, 1998). Micromorphological analyses also established that one room in a small building within the industrial precinct was clearly identifiable as a living room, as the floors were repeatedly plastered and covered in thin lenses of low-temperature ash and burned bone from food cooking. Beneath this floor, a potter was buried with a potter's wheel, and so it is likely that there had been an increased shift toward professional craft specialization, ca. 2500 BCE, with specialists in this instance resident within industrial precincts and not within residential neighborhoods elsewhere on the site.

At other sites, more recent integrated geoarchaeological analysis has identified high-temperature burning, >1,000 °C, associated with casting pits for bronze working (Berna et al., 2007) and iron production in the Iron Age levels at Tel Dor, Israel (Eliyahu-Behar et al., 2008).

Open areas and middens

Significant areas of tell sites were also used as open areas and middens, which have been less intensively studied than houses and buildings until recently. Open areas and middens are likely to have been important loci for activities such as animal penning, craft activities, food processing and preparation, as well as social interaction and are key to understanding past communities and life ways. As many buildings were often kept relatively clean, dirtier open areas and middens also provide an opportunity to investigate a rich inventory of materials used and discarded by communities, as well as their sequence and history, especially where deposition is rapid as materials are often better preserved if only exposed for short periods of time (Mallol et al., 2007).

One of the most recent multi-scalar geoarchaeological analyses of middens is that conducted by Shillito at the Neolithic site of Çatalhöyük where clusters of buildings are separated by extensive midden areas and some buildings may become receptacles for refuse at the end of their use life (Shillito, 2011; Shillito and Matthews, 2013). Field, micromorphological, and micro-IR analyses were combined with high-precision spot sampling for analysis of plant phytoliths and identification of coprolites by GC-MS to investigate the diverse materials accumulated within the middens as well as assess the activities represented. Many periodic and occasionally cyclical residues from specific activities were identified that have important implications for resource use and management of the built environment. Residues in these middens included discarded remains of fuel rake-outs from hearths and ovens, floor sweepings, food processing debris including wheat husks and lenses with abraded rock fragments from the use of grindstones, specific crafts such as wood working, and human coprolites, which are being studied for high-resolution variation in diet (Shillito et al., 2011). Occasionally, there is evidence for periodic in situ activities, such as production of fired lime in the early levels and probable bonfires for pottery firing in later levels, as well as pits for extraction of ashy materials for mortar and brick additives. The finely stratified lenses and remarkable preservation of many materials suggest frequent discard and rapid burial. There are few indications of erosion and long-term exposure; rare exceptions include a bioturbated layer early in the history of the site when it may have been less populated.

Open areas and middens are currently the subject of increased geoarchaeological analyses: examples include several sites in the Central Zagros in Iraq and Iran (Matthews et al., 2013b); Aşıklı Höyük in Central Anatolia, where there is a long sequence of in situ activity areas followed by middens and traces of animal pens (Stiner et al. 2014); and Neolithic-Bronze Age sites in Greece (Koromila, 2012; Kyrillidhou, 2012).

Streets and lanes

Many tell sites include systems of streets and lanes that provide key information on social and economic networks as well as internal settlement organization. Radiating from tells in northern Mesopotamia, in particular, are a series of routeways detectable by remote sensing and field observations as holloways, which have enabled study of hierarchies in the connectivity of sites (Wilkinson et al., 2010; Ur et al., 2013). Geoarchaeological analysis of cross sections through these holloways established that they were infilled by low-energy deposits that were subject to periodic wetting and drying and then reworking by bioturbation and that they were probably initially formed during the 4th millennium BCE when Tell Brak was a major city and center of international trade surrounded by smaller sites.

Micromorphological analyses have established that some streets and lanes were surfaced and well maintained, notably those adjacent to the ceremonial complex at the early Neolithic site of Aşıklı Höyük, Turkey, where the street was repeatedly surfaced with pebbles and kept very clean (Esin and Harmankaya, 1999). At other sites, away from ceremonial areas, streets and lanes were not frequently paved and were used periodically for discard as at Çatalhöyük (Shillito and Ryan, 2013), Abu Salabikh (Matthews and Postgate, 1994), and Tell Brak (Matthews et al., 2001). At the early Neolithic site of Sheikh-e Abad, as noted above, micromorphological and GC-MS identification of widespread traces of non-burned ruminant dung in lanes and open areas indicates that animals were brought within the settlement and lived in close proximity to humans in this early settlement, ca. 7600 BCE (Matthews et al., 2013b).

Natural deposits and postdepositional alterations

Natural depositional agencies and postdepositional alterations on tells may be ongoing both during and post-occupation, but as Butzer (1982) highlights, they will generally have their greatest impact during periods of population decline or abandonment (as at Tell Brak discussed above) and during extreme natural events such as major flooding or tsunamis (see Bruins et al., 2008). Smaller-scale accumulations of natural deposits laid down during episodes of periodic disuse have been observed through micromorphological analysis. One example is an oven on a flat rooftop at Çatalhöyük discussed above (Figure 6), within which were found periodic accumulations of rainwash from probable seasonal disuse. Conversely, anthropogenic deposits are more abundant than natural deposits during periods of population expansion and intensive human activity. Many materials are better preserved when they are rapidly buried by either natural or anthropogenic deposits, as they are exposed for less time to microbial action and to physical disturbance from wind, water, humans, animals, and plant roots, as observed in ethnoarchaeological studies (Mallol et al., 2007).

The nature and extent of natural postdepositional alterations and preservation of materials on tells is dependent upon many factors, and understanding their effects requires interdisciplinary research and collaboration in studies of soil science, microbiology, chemistry, conservation, and paleoclimate/environment, to identify the diverse parameters, agents, and processes affecting organic and inorganic materials. The climate and environment of tells vary geographically from temperate in Hungary, for example, to semiarid in Turkey and to desertic in regions of Sudan; there are also temporal variations: seasonally, annually, and over longer periods. Burial environments also vary topographically within tells themselves, and they may differ significantly at very small scales and time intervals, between and within strata, according to composition, pH, oxidation state, and hydrology. The base of many tells and indeed entire low mounds may be covered by extensive alluvium and colluvium, which in some regions may be up to 4 m or more thick as at Çatalhöyük (Boyer et al., 2006).

In summary, in the semiarid environments where most tells are located, the principal natural agencies and processes affecting them that have been identified by field observation, micromorphology, and elemental, mineralogical, and organic geochemical analyses include (1) organic decay from microbial action in oxidizing conditions that result in the loss of perishable materials, subsequent reduction in the volume and depth of deposits, and deposition of amorphous organic staining; (2) physical disturbance and reworking of deposit structures by burrowing insects, microfauna, animals, and plant or tree roots (Courty and Weiss, 1997; Davidson et al., 2010); (3) dissolution and reprecipitation of salts (gypsum and sodium salts; Maghsoudi et al., 2014) as well as carbonates due to evaporation at the surface or point of contact with plant roots during transpiration; (4) formation of other new or altered minerals such as vivianite in phosphate- and iron-rich deposits and transformation of ash (Weiner, 2010); (5) occasional translocation of fine materials and redeposition, often along edges of voids by water movement; and (6) surface erosion and deposition by wind and water, for example, which may significantly alter the form and height of tells (Rosen, 1986; Davidson et al., 2010).

One of the challenges in excavating tells is identifying intact mudbrick or terre pisé walls, as these are often leveled or eroded and surrounded by collapse or redeposited sediments of the same material. Ethnoarchaeological and geoarchaeological studies are contributing significantly to our understanding of these processes and to detection of both in situ and redeposited construction materials (Friesem et al., 2011).

Cultural postdepositional alterations identified by geoarchaeological analyses at tells include (1) maintenance and cleaning practices, attested by the impressions or remains of mats on floors, sparsity of residues on floors within many houses, and subrounded plaster aggregates from sweeping found within lenses on floors or discarded in hearths or in middens; (2) trampling and physical reworking of deposit components and layers; (3) burning; (4) leveling and remodeling of features, such as horizons with fragments of oven superstructure; (5) dismantling, infilling, leveling, or destruction of buildings; and (6) digging of pits. After abandonment of sites, there is also evidence that tells may be reused as burial grounds or their materials mined for manure and building materials, as well as impacted by plowing, cultivation of crops and tree plantations, grazing of animals, construction of dams and flooding of tells and their landscapes, and illicit looting.

In general, however, many deposits, materials, and features are better preserved in repeatedly occupied tell sites than in single period or shifting occupation in flatter sites because deposition and burial of materials on tell sites is more rapid. Deposits and materials are also better preserved in the oxidized environments of many tell sites in semiarid regions, than those of many sites in temperate regions, where postdepositional processes are accelerated and more marked. Exceptional preservation within tells can occur in arid regions such as Sudan, where many organic materials are well preserved due to the absence of moisture that enables destructive microbial activity (van der Veen, 2007), as well as in waterlogged or locally anaerobic conditions (e.g., from rapid burial by clay-rich materials) within or at the base of mounds due to limited exposure to microbial action (Matthews, 2005a).

Conclusions

One of the great challenges in geoarchaeological analyses of tells is identifying the diversity of materials present and the different agencies and pathways that affect their origin, deposition, and postdepositional alterations. These challenges, however, are at the very heart of archaeology itself, and addressing and examining them requires interdisciplinary multi-scalar approaches and collaboration, as well as consideration of cultural as well as natural agencies. The examples and case studies documented here illustrate the ways in which geoarchaeology is contributing to new high-resolution contextual analysis of a wide range of architectural, bioarchaeological, and micro-artifactual materials on tells and answering key research questions on the ecological and social strategies and histories of the individuals and communities who constructed and occupied them. Future research requires further ethnoarchaeological and experimental research to continue to advance our understanding of past built environments and development and dissemination of reference materials. Geoarchaeological analyses of materials and sites provide crucial data that are relevant to conservation and preservation of artifacts and sites, and further collaborations should also be developed in these fields.

Bibliography

Albert, R. M., Shahack-Gross, R., Cabanes, D., Gilboa, A., Lev-Yadun, S., Portillo, M., Sharon, I., Boaretto, E., and Weiner, S., 2008. Phytolith-rich layers from the Late Bronze and Iron Ages at Tel Dor (Israel): mode of formation and archaeological significance. *Journal of Archaeological Science*, **35**(1), 57–75.

Anderson, S., and Ertuğ-Yaraş, F., 1998. Fuel fodder and faeces: an ethnographic and botanical study of dung fuel use in central Anatolia. *Environmental Archaeology: The Journal of Palaeoecology*, **1**, 99–110.

Anderson, E., Almond, M. J., Matthews, W., Cinque, G. C., and Frogley, M. D., 2014. Analysis of red pigments from the Neolithic sites of Çatalhöyük in Turkey and Sheikh-e Abad in Iran. *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy*, **131**, 373–383.

Balbo, A. L., Iriarte, E., Arranz, A., Zapata, L., Lancelotti, C., Madella, M., Teira, L., Jiménez, M., Braemer, F., and Ibáñez, J. J., 2012. Squaring the circle. Social and environmental implications of Pre-Pottery Neolithic building technology at Tell Qarassa (South Syria). *PLoS ONE*, **7**(7), e42109.

Bayliss, A., and Farid, S., 2012. Modelling chronology. *Catalhoyuk 2012 Archive Report*, pp. 236–237. http://www.catalhoyuk.com/downloads/Archive_Report_2012.pdf.

Berge, M. A., and Drahor, M. G., 2011. Electrical resistivity tomography investigations of multilayered archaeological settlements: part II – a case from Old Smyrna Höyük, Turkey. *Archaeological Prospection*, **18**(4), 291–302.

Berna, F., Behar, A., Shahack-Gross, R., Berg, J., Boaretto, E., Gilboa, A., Sharon, I., Shalev, S., Shilstein, S., Yahalom-Mack, N., Zorn, J. R., and Weiner, S., 2007. Sediments exposed to high temperatures: reconstructing pyrotechnological processes in Late Bronze and Iron Age strata at Tel Dor (Israel). *Journal of Archaeological Science*, **34**(3), 358–373.

Bloch, M., 2010. Is there religion at Catalhoyuk. . .or are there just houses? In Hodder, I. (ed.), *Religion in the Emergence of Civilization: Çatalhöyük as a Case Study*. Cambridge: Cambridge University Press, pp. 146–162.

Boivin, N. L., 2000. Life rhythms and floor sequences: excavating time in rural Rajasthan and Neolithic Çatalhöyük. *World Archaeology*, **31**(3), 367–388.

Boyer, P., Roberts, N., and Baird, D., 2006. Holocene environment and settlement on the Çarşamba alluvial fan, south-central Turkey: integrating geoarchaeology and archaeological field survey. *Geoarchaeology*, **21**(7), 675–698.

Brochier, J., Villa, P., Giacomarra, M., and Tagliacozzo, A., 1992. Shepherds and sediments: geo-ethnoarchaeology of pastoral sites. *Journal of Anthropological Archaeology*, **11**(1), 47–102.

Bruins, H. J., MacGillivray, J. A., Synolakis, C. E., Benjamini, C., Keller, J., Kisch, H. J., Klügel, A., and van der Plicht, J., 2008. Geoarchaeological tsunami deposits at Palaikastro (Crete) and the Late Minoan IA eruption of Santorini. *Journal of Archaeological Science*, **35**(1), 191–212.

Bull, I. D., Elhmmali, M. M., Perret, V., Matthews, W., Roberts, D. J., and Evershed, R. P., 2005. Biomarker evidence of faecal deposition in archaeological sediments at Çatalhöyük. In Hodder, I. (ed.), *Inhabiting Çatalhöyük: Reports from the 1995–99 Seasons*. Cambridge: The McDonald Institute for Archaeological Research. British Institute of Archaeology at Ankara Monograph 38. Çatalhöyük Research Project, Vol. 4, pp. 415–420. London: British Institute of Archaeology at Ankara.

Butzer, K. W., 1982. *Archaeology as Human Ecology: Method and Theory for a Contextual Approach*. Cambridge: Cambridge University Press.

Canti, M., 1995. A mixed-method approach to geoarchaeological analysis. In Barham, A. J., and Macphail, R. I. (eds.), *Archaeological Sediments and Soils: Analysis, Interpretation and Management*. London: Institute of Archaeology, pp. 183–190.

Canti, M., 1999. The production and preservation of faecal spherulites: animals, environment and taphonomy. *Journal of Archaeological Science*, **26**(3), 251–258.

Cessford, C., 2007. Neolithic Excavations in the North Area, East Mound, Çatalhöyük 1995–98. In Hodder, I. (ed.), *Excavating Çatalhöyük: South, North and KOPAL Area Reports from the 1995–99 Seasons*. Cambridge: McDonald Institute for Archaeological Research. British Institute of Archaeology at Ankara Monograph 37. Çatalhöyük Research Project, Vol. 3, pp. 345–549. London: British Institute of Archaeology at Ankara.

Courty, M.-A., and Weiss, H., 1997. The scenario of environmental degradation in the Tell Leilan region, NE Syria, during the late third millennium abrupt climate change. In Dalfes, H. N., Kukla, G., and Weiss, H. (eds.), *Third Millennium BC Climate Change and Old World Collapse*. Berlin: Springer. NATO ASI Series, Global Environmental Change 49, pp. 107–148.

Courty, M. A., Goldberg, P., and Macphail, R. I., 1989. *Soils and Micromorphology in Archaeology*. Cambridge: Cambridge University Press.

Creekmore, A., 2010. The structure of upper Mesopotamian cities: insight from fluxgate gradiometer survey at Kazane Höyük, southeastern Turkey. *Archaeological Prospection*, **17**(2), 73–88.

Dalfes, H. N., Kukla, G., and Weiss, H. (eds.), 1997. *Third Millennium BC Climate Change and Old World Collapse*. Berlin: Springer. NATO ASI Series, Global Environmental Change 49.

David, N., and Kramer, C., 2001. *Ethnoarchaeology in Action*. Cambridge: Cambridge University Press.

Davidson, D. A., and Shackley, M. L., 1976. *Geoarchaeology: Earth Science and the Past*. London: Duckworth.

Davidson, D. A., Wilson, C. A., Lemos, I. S., and Theocharopoulos, S. P., 2010. Tell formation processes as indicated from geoarchaeological and geochemical investigations at Xeropolis, Euboea, Greece. *Journal of Archaeological Science*, **37**(7), 1564–1571.

Deckers, K. (ed.), 2011. *Holocene Landscapes Through Time in the Fertile Crescent. Subartu XXVIII*. Turnhout: Brepols.

DeMenocal, P. B., 2001. Cultural responses to climate change during the late Holocene. *Science*, **292**(5517), 667–673.

Djamali, M., Akhani, H., Andrieu-Ponel, V., Braconnot, P., Brewer, S., de Beaulieu, J.-L., Fleitmann, D., Fleury, J., Gasse, F., Guibal, F., Jackson, S. T., Lézine, A.-M., Médail, F., Ponel, P., Roberts, N., and Stevens, L., 2010. Indian summer monsoon variations could have affected the early-holocene woodland expansion in the Near East. *The Holocene*, **20**(5), 813–820.

Eliyahu-Behar, A., Shilstein, S., Raban-Gerstel, N., Goren, Y., Gilboa, A., Sharon, I., and Weiner, S., 2008. An integrated approach to reconstructing primary activities from pit deposits: iron smithing and other activities at Tel Dor under Neo-Assyrian domination. *Journal of Archaeological Science*, **35**(11), 2895–2908.

Elliott, S., Bendrey, R., Whitlam, J., Rauf Aziz, K., and Evans, J., (2015). Preliminary ethnoarchaeological research on modern animal husbandry in Bestansur, Iraqi Kurdistan: integrating animal, plant and environmental data. *Environmental Archaeology: The Journal of Human Palaeoecology* **20**(3), 283–303.

Emery, V. L., and Morgenstein, M., 2007. Portable EDXRF analysis of a mud brick necropolis enclosure: evidence of work organization, El Hibeh, Middle Egypt. *Journal of Archaeological Science*, **34**(1), 111–122.

Esin, U., and Harmankaya, S., 1999. Aşıklı. In Özdoğan, M., and Başgelen, N. (eds.), *Neolithic in Turkey: The Cradle of Civilization*. Istanbul: Arkeoloji ve Sanat Yayınları, pp. 115–132.

Farid, S., 2000. The excavation process at Çatalhöyük. In Hodder, I. (ed.), *Towards Reflexive Method in Archaeology: The Example* *at Çatalhöyük*. Cambridge: McDonald Institute for Archaeological Research, University of Cambridge. British Institute of Archaeology at Ankara, Monograph 28. Çatalhöyük Research Project, Vol. 2, pp. 19–38.

Fortin, M., and Aurenche, O., 1998. *Espace naturel, espace habité en Syrie du Nord (10e–2e millénaires av. J-C.), Natural Space, Inhabited Space in Northern Syria (10th–2nd millennium B. C.), Actes du colloque, université de Laval (Québec), 5–7 mai 1997*. Travaux de la Maison de l'Orient 28. Québec and Lyon: Canadian Society for Mesopotamian Studies and Maison de l'Orient Méditerranéen.

Frahm, E., and Doonan, R. C. P., 2013. The technological versus methodological revolution of portable XRF in archaeology. *Journal of Archaeological Science*, **40**(2), 1425–1434.

Friesem, D., Boaretto, E., Eliyahu-Behar, A., and Shahack-Gross, R., 2011. Degradation of mud brick houses in an arid environment: a geoarchaeological model. *Journal of Archaeological Science*, **38**(5), 1135–1147.

García-Suárez, A., 2014. Micromorphology: a high-resolution investigation of Neolithic intra- and inter-site relationships. In Haddow, S. D. (comp.), *Çatalhöyük 2014 Archive Report*, pp. 208–210. http://www.catalhoyuk.com/downloads/Archive_Report_2014.pdf.

Gasche, H., and Tanret, M., 1998. *Changing Watercourses in Babylonia: Towards a Reconstruction of the Ancient Environment in Lower Mesopotamia*. Ghent: University of Ghent and the Oriental Institute, Chicago.

Gliozzo, E., Damiani, D., Camporeale, S., Memmi, I., and Papi, E., 2011. Building materials from Thamusida (Rabat, Morocco): a diachronic local production from the Roman to the Islamic period. *Journal of Archaeological Science*, **38**(5), 1026–1036.

Gur-Arieh, S., Shahack-Gross, R., Maeir, A. M., Lehmann, G., Hitchcock, L. A., and Boaretto, E., 2014. The taphonomy and preservation of wood and dung ashes found in archaeological cooking installations: case studies from iron age Israel. *Journal of Archaeological Science*, **46**, 50–67.

Heyvaert, V. M. A., Walstra, J., Verkinderen, P., Weertz, H. J. T., and Ooghe, B., 2010. The role of human interference on the channel shifting of the Karkheh River in the Lower Khuzestan plain (Mesopotamia, SW Iran). *Quaternary International*, **251**, 52–63.

Hicks, D., and Beaudry, M. C. (eds.), 2010. *The Oxford Handbook of Material Culture Studies*. Oxford: Oxford University Press.

Hodder, I., 1987. The meaning of discard: Ash and domestic space in Baringo. In Kent, S. (ed.), *Method and Theory for Activity Area Research: An Ethnoarchaeological Approach*. New York: Columbia University Press, pp. 424–448.

Hodder, I., 1999. *The Archaeological Process: An Introduction*. Oxford: Blackwell.

Hodder, I., 2010. *Religion in the Emergence of Civilization: Catalhoyuk as a Case-study*. Cambridge: Cambridge University Press.

Houben, H., and Guillaud, H., 1989. *Earth Construction: A Comprehensive Guide*. London: Intermediate Technology Publications.

InterArchive, 2012. http://www.york.ac.uk/archaeology/research/current-projects/interarchive/.

Karkanas, P., and Van de Moortel, A., 2014. Micromorphological analysis of sediments at the Bronze Age site of Mitrou, central Greece: patterns of floor construction and maintenance. *Journal of Archaeological Science*, **43**, 198–213.

Karkanas, P., Dabney, M. K., Smith, R. A. K., and Wright, J. C., 2012. The geoarchaeology of Mycenaean chamber tombs. *Journal of Archaeological Science*, **39**(8), 2722–2732.

Kingery, D. W., Vandiver, P. B., and Prickett, M., 1988. The beginnings of pyrotechnology, part II: production and use of lime and gypsum plaster in the Pre-Pottery Neolithic Near East. *Journal Field Archaeology*, **15**(2), 219–244.

Koromila, G., 2012. From human practice to archaeological sediments: a geoarchaeological study of open spaces in Neolithic Greece. Poster presented at the International Conference 'Early Farmers: The View from Archaeology and Science', Department of Archaeology and Conservation, Cardiff University, 14–16 May 2012. Program and Abstracts, p. 34 http://www.cardiff.ac.uk/share/resources/Early%20Farmers_Final%20programme%20and%20abstracts.pdf.

Kramer, C., 1979. An archaeological view of a contemporary Kurdish village: domestic architecture, household size, and wealth. In Kramer, C. (ed.), *Ethnoarchaeology: Implications of Ethnography for Archaeology*. New York: Columbia University Press, pp. 139–163.

Kyrillidou, S., 2012. Settlement micromorphology and the geoarchaeology of houses and households. Poster presented at the International Conference 'Early Farmers: The View from Archaeology and Science', Department of Archaeology and Conservation, Cardiff University, 14–16 May 2012. Program and Abstracts, pp. 34–35 http://www.cardiff.ac.uk/share/resources/Early%20Farmers_Final%20programme%20and%20abstracts.pdf.

Leatherbarrow, D., and Mostafavi, M., 2002. *Surface Architecture*. Cambridge, MA: MIT Press.

Love, S., 2012. The geoarchaeology of mudbricks in architecture: a methodological study from Çatalhöyük, Turkey. *Geoarchaeology*, **27**(2), 140–156.

Maghsoudi, M., Simpson, I. A., Kourampas, N., and Nashli, H. F., 2014. Archaeological sediments from settlement mounds of the Sagzabad Cluster, central Iran: human-induced deposition on an arid alluvial plain. *Quaternary International*, **324**, 67–83.

Mallol, C., Marlowe, F. W., Wood, B. M., and Porter, C. C., 2007. Earth, wind, and fire: ethnoarchaeological signals of Hadza fires. *Journal of Archaeological Science*, **34**(12), 2035–2052.

Matthews, R., 1996. Surface scraping and planning. In Hodder, I. (ed.), *On the Surface: Catalhoyuk 1993–95*. Cambridge: McDonald Institute for Archaeological Research. British Institute of Archaeology at Ankara Monograph 22. Çatalhöyük Research Project, Vol. 1, pp. 79–100. London: British Institute of Archaeology at Ankara.

Matthews, R., 2003a. *Excavations at Tell Brak*. Cambridge/London: The McDonald Institute of Archaeological Research/The British School of Archaeology in Iraq. Exploring an Upper Mesopotamian Regional Centre, 1994–1996, Vol. 4.

Matthews, W., 2003b. Microstratigraphic sequences: indications of uses and concepts of space. In Matthews, R. J. (ed.), *Excavations at Tell Brak*. Cambridge/London: The McDonald Institute of Archaeological Research/The British School of Archaeology in Iraq. Exploring an Upper Mesopotamian Regional Centre, 1994–1996, Vol. 4, pp. 377–388.

Matthews, W., 2005a. Micromorphological and microstratigraphic traces of uses and concepts of space. In Hodder, I. (ed.), *Inhabiting Çatalhöyük: Reports from the 1995–99 Seasons*. Cambridge: McDonald Institute for Archaeological Research. British Institute of Archaeology at Ankara Monograph 38. Çatalhöyük Research Project, Vol. 4, pp. 355–398. London: British Institute of Archaeology, 553–572.

Matthews, W., 2005b. Life-cycle and life-course of buildings. In Hodder, I. (ed.), *Çatalhöyük Perspectives. Themes from the 1995–99 Seasons*. Cambridge: McDonald Institute for Archaeological Research. British Institute of Archaeology at Ankara Monograph 40. Çatalhöyük Research Project, Vol. 6, pp. 125–151. London: British Institute of Archaeology at Ankara.

Matthews, W., 2010. Geoarchaeology and taphonomy of plant remains and microarchaeological residues in early urban environments in the Ancient Near East. *Quaternary International*, **214**(1–2), 98–113.

Matthews, W., 2012. Household life-histories and boundaries: microstratigraphy and micromorphology of architectural surfaces in Building 3 BACH. In Tringham, R., and Stevanovic, M. (eds.), *Last House on the Hill: BACH Area Reports from Çatalhöyük*. Los Angeles: Cotsen Institute of Archaeology Press. Catalhoyuk 11, pp. 205–223. Monumenta Archaeologica 27.

Matthews, W., and French, C. A. I., 2005. Domestic space at Saar: The microstratigraphic evidence. In Killick, R., and Moon, J. (eds.), *The Early Dilmun Settlement at Saar*. Ludlow: Archaeology International, pp. 325–337.

Matthews, W., and Postgate, J. N., with, Payne, S., Charles, M. P., and Dobney, K., 1994. The imprint of living in a Mesopotamian city: questions and answers. In Luff, R., and Rowley Conwy, P. (eds.), *Whither Environmental Archaeology?* Oxford: Oxbow Books, pp. 171–212.

Matthews, W., French, C. A. I., Lawrence, T., and Cutler, D., 1996. Multiple surfaces: the micromorphology. In Hodder, I. (ed.), *On the Surface: Çatalhöyük 1993–95*. Cambridge: McDonald Institute for Archaeological. British Institute of Archaeology at Ankara Monograph 22. Çatalhöyük Research Project, Vol. 1, pp. 301–342. London: British Institute of Archaeology at Ankara.

Matthews, W., French, C. A. I., Lawrence, T., Cutler, D. F., and Jones, M. K., 1997a. Microstratigraphic traces of site formation processes and human activities. *World Archaeology*, **29**(2), 281–308.

Matthews, W., French, C. A. I., Lawrence, T., Cutler, D., and Jones, M., 1997b. Activities inside the temple: the evidence of microstratigraphy. In Crawford, H. E. W., Killick, R. G., and Moon, J. (eds.), *The Dilmun Temple at Saar: Bahrain and its Archaeological Inheritance*. New York: Kegan Paul International, pp. 31–46.

Matthews, W., Hastorf, C. A., and Ergenekon, B., with contributions from Erkal, A., Yalman, N., Ağcabay, M., Aydinoğlu, B., Bartu, A., Baysal, A., Boz, B., Middleton, W., Near, J., Rosen, A., and Stevanovic, M., 2000a. Ethnoarchaeology: studies in local villages aimed at understanding aspects of the Neolithic site. In Hodder, I. (ed.), *Towards Reflexive Method in Archaeology: The Example at Çatalhöyük*. Cambridge: McDonald Institute of Archaeological Research, and London: British Institute of Archaeology at Ankara. British Institute of Archaeology at Ankara Monograph 28. Çatalhöyük Research Project volume 2, pp. 177–188.

Matthews, W., Hastorf, C., Andrews, P., and Molleson, T., 2000b. Integrating archaeological science. In Hodder, I. (ed.), *Towards Reflexive Method in Archaeology: The Example at Çatalhöyük*. Cambridge: McDonald Institute of Archaeological Research. British Institute of Archaeology at Ankara Monograph 28. Çatalhöyük Research Project, Vol. 2, pp. 37–50. London: British Institute of Archaeology at Ankara.

Matthews, W., French, C. A. I., Lawrence, T., Cutler, D. F., and Jones, M. K., 2001. Microstratigraphic analysis of depositional sequences in Areas FS and SS. In Oates, D., Oates, J., and McDonald, H. (eds.), *Excavations at Tell Brak*. Cambridge/London: McDonald Institute for Archaeological Research/British School of Archaeology in Iraq. Nagar in the Third Millennium BC, Vol. 2, pp. 353–367.

Matthews, R., Matthews, W., and Mohammadifar, Y. (eds.), 2013a. *The Earliest Neolithic of Iran: 2008 Excavations at Sheikh-e Abad and Jani: The Central Zagros Archaeological Project*. Oxford: Oxbow Books. British Institute of Persian Studies Archaeological Monograph IV, Vol. I.

Matthews, W., Almond, M. J., Anderson, E., Wiles, J., and Williams, H., 2013b. Biographies of architectural materials and buildings: integrating new high-resolution micro-analysis and geochemistry. In Hodder, I. (ed.), *Substantive Technologies at Çatalhöyük: Reports from the 2000–2008 Seasons*. Los Angeles: Cotsen Institute of Archaeology Press. British Institute of Archaeology at Ankara Monograph 48. Çatalhöyük Research Project, Vol. 9, pp. 115–136. Monumenta Archaeologica 31, London: British Institute at Ankara.

Matthews, W., with contributions from Shillito, L-M., and Elliott, S., 2013b. Investigating early Neolithic materials, ecology and sedentism: micromorphology and microstratigraphy. In Matthews, R. J., Matthews, W., and Mohammadifar, Y. (eds.), *The Earliest Neolithic of Iran: 2008 Excavations at Sheikh-e Abad and Jani: The Central Zagros Archaeological Project*. Oxford: Oxbow Books. British Institute of Persian Studies Archaeological Monograph IV, Vol. I, pp. 67–104.

Matthews, W., Shillito, L.-M., Elliott, S., Bull, I. D., and Williams, J., 2014. Neolithic lifeways: microstratigraphic traces within houses, animal pens and settlements. In Whittle, A. W. R., and Bickle, P. (eds.), *Early Farmers: The View from Archaeology and Science*. Oxford: Oxford University Press. Proceedings of the British Academy, Vol. 198, pp. 251–279.

McAnany, P. A., and Hodder, I., 2009. Thinking about stratigraphic sequence in social terms. *Archaeological Dialogues*, **16**(1), 1–22.

McKellar, J. A., 1983. Correlations and the explanation of distributions. *Atlatl: Arizona Anthropologist*, **4**, 2–5.

Mentzer, S. M., 2014. Microarchaeological approaches to the identification and interpretation of combustion features in prehistoric archaeological sites. *Journal of Archaeological Method and Theory*, **21**(3), 616–668.

Mentzer, S. M., and Quade, J., 2013. Compositional and isotopic analytical methods in archaeological micromorphology. *Geoarchaeology*, **28**(1), 87–97.

Menze, B. H., and Ur, J. A., 2012. Mapping patterns of long-term settlement in northern Mesopotamia at a large scale. *Proceedings of the National Academy of Sciences*, **109**(14), 778–787.

Meyer, J.-W., 2007. Veränderungen der Grabungsstrategie in Tell Chuera (Syrien) aufgrund der Ergebnisse der geomagnetischen Prospektion. In Posselt, M., Zickgraf, B., and Dobiat, C. (eds.), *Geophysik und Ausgrabung. Einsatz und Auswertung zerstörungsfreier Prospektion in der Archäologie. Internationale Archäologie*. Rahden: Leidorf. Naturwissenschaft und Technologie, Vol. 6, pp. 223–236.

Middleton, W. D., Price, T. D., and Meiggs, D. C., 2005. Chemical analysis of floor sediments for the identification of anthropogenic activity residues. In Hodder, I. (ed.), *Inhabiting Çatalhöyük: Reports from the 1995–99 Seasons*. Cambridge: The McDonald Institute for Archaeological Research. British Institute of Archaeology at Ankara Monograph 38. Çatalhöyük Research Project, Vol. 4, pp. 399–412. London: British Institute of Archaeology at Ankara.

Miller, N. F., 1996. Seed eaters of the ancient Near East: human or herbivore. *Current Anthropology*, **37**(3), 521–528.

Namdar, D., Zukerman, A., Maeir, A. M., Katz, J. C., Cabanes, D., Trueman, C., Shahack-Gross, R., and Weiner, S., 2011. The 9th century BCE destruction layer at Tell es-Safi/Gath, Israel: integrating macro- and microarchaeology. *Journal of Archaeological Science*, **38**(12), 3471–3482.

Nesbitt, M., 1993. Archaeobotanical evidence for early Dilmun diet at Saar, Bahrain. *Arabian Archaeology and Epigraphy*, **4**(1), 20–47.

Nodarou, E., Frederick, C., and Hein, A., 2008. Another (mud)brick in the wall: scientific analysis of bronze age earthen construction materials from East Crete. *Journal of Archaeological Science*, **35**(11), 2997–3015.

Oates, D., Oates, J., and McDonald, H., 2001. *Excavations at Tell Brak*. Cambridge/London: McDonald Institute for Archaeological Research/British School of Archaeology in Iraq. Nagar in the Third Millennium BC, Vol. 2.

Parker, B. J., and Foster, C. P. (eds.), 2012. *New Perspectives on Household Archaeology*. Winona Lake: Eisenbrauns.

Pfälzner, P., Niehr, H., Pernicka, E., Lange, S., and Köster, T. (eds.), 2013. *Contextualising Grave Inventories in the Ancient Near East. Proceedings of a Workshop at the London 7th ICAANE in April 2010 and an International Symposium in Tübingen in November 2010, both Organised by the Tübingen Post-Graduate School "Symbols of the Dead."* Wiesbaden: Harrassowitz. Qatna Studien, Supplementa Bd. 3.

Portillo, M., Kadowaki, S., Nishiaki, Y., and Albert, R. M., 2014. Early neolithic household behavior at Tell Seker al-Aheimar (Upper Khabur, Syria): a comparison to ethnoarchaeological study of phytoliths and dung spherulites. *Journal of Archaeological Science*, **42**, 107–118.

Postgate, J. N., 1992. *Early Mesopotamia: Society and Economy at the Dawn of History*. London: Routledge.

Pournelle, J. R., 2007. KLM to CORONA: a bird's-eye view of cultural ecology and early Mesopotamian urbanization. In Stone, E. C. (ed.), *Settlement and Society: Essays Dedicated to Robert McCormick Adams*. Los Angeles: Cotsen Institute of Archaeology, pp. 29–62. Chicago: Oriental Institute.

Rainville, L., 2005. *Investigating Upper Mesopotamian Households Using Micro-Archaeological Techniques*. Oxford: Archaeopress. British Archaeological Reports, International Series, Vol. 1368.

Regev, L., Poduska, K. M., Addadi, L., Weiner, S., and Boaretto, E., 2010a. Distinguishing between calcites formed by different mechanisms using infrared spectrometry: archaeological applications. *Journal of Archaeological Science*, **37**(12), 3022–3029.

Regev, L., Zukerman, A., Hitchcock, L., Maeir, A. M., Weiner, S., and Boaretto, E., 2010b. Iron age hydraulic plaster from Tell es-Safi/Gath, Israel. *Journal of Archaeological Science*, **37**(12), 3000–3009.

Renfrew, C., 1976. Archaeology and the Earth sciences. In Davidson, D. A., and Shackley, M. L. (eds.), *Geoarchaeology: Earth Science and the Past*. London: Duckworth, pp. 1–5.

Robb, J., 2010. Beyond agency. *World Archaeology*, **42**(4), 493–520.

Rosen, A. M., 1986. *Cities of Clay. The Geoarchaeology of Tells*. Chicago: University Press of Chicago.

Rosen, A. M., 1992. Preliminary identification of silica skeletons from Near Eastern archaeological sites: an anatomical approach. In Rapp, G. R., and Mulholland, S. C. (eds.), *Phytolith Systematics: Emerging Issues*. New York: Plenum Press. Advances in Archaeological and Museum Science, Vol. 1, pp. 129–147.

Saeedi, S., 2010. Microdebris analysis. In Pollock, S., Bernbeck, R., and Abdi, K. (eds.), *The 2003 Excavations at Tol-e Baši, Iran: Social Life in a Neolithic Village*. Mainz: Verlag Philipp von Zabern. Archäologie in Iran und Turan, Vol. 10, pp. 246–255.

Schiffer, M. B., 1987. *Formation Processes of the Archaeological Record*. Albuquerque: University of New Mexico Press.

Shahack-Gross, R., 2011. Herbivorous livestock dung: formation, taphonomy, methods for identification, and archaeological significance. *Journal of Archaeological Science*, **38**(2), 205–218.

Shahack-Gross, R., and Ayalon, A., 2013. Stable carbon and oxygen isotopic compositions of wood ash: an experimental study with archaeological implications. *Journal of Archaeological Science*, **40**(1), 570–578.

Shahack-Gross, R., Albert, R.-M., Gilboa, A., Nagar-Hilman, O., Sharon, I., and Weiner, S., 2005. Geoarchaeology in an urban context: the uses of space in a Phoenician monumental building at Tel Dor (Israel). *Journal of Archaeological Science*, **32**(9), 1417–1431.

Shillito, L.-M., 2011. *Daily Activities, Diet and Resource Use at Neolithic Çatalhöyük: Microstratigraphic and Biomolecular Evidence from Middens*. Oxford: Archaeopress. British Archaeological Reports, International Series, Vol. 2232.

Shillito, L.-M., 2013. Grains of truth or transparent blindfolds? A review of current debates in archaeological phytolith analysis. *Vegetation History and Archaeobotany*, **22**(1), 71–82.

Shillito, L.-M., and Matthews, W., 2013. Geoarchaeological investigations of midden-formation processes in the early to late ceramic Neolithic levels at Çatalhöyük, Turkey *ca*. 8550–8370 cal BP. *Geoarchaeology*, **28**(1), 25–49.

Shillito, L.-M., and Ryan, P., 2013. Surfaces and streets: phytoliths, micromorphology and changing use of space at Neolithic Çatalhöyük (Turkey). *Antiquity*, **87**(337), 684–700.

Shillito, L.-M., Bull, I. D., Matthews, W., Almond, M. J., Williams, J. M., and Evershed, R. P., 2011. Biomolecular and micromorphological analysis of suspected faecal deposits at Neolithic Çatalhöyük, Turkey. *Journal of Archaeological Science*, **38**(8), 1869–1877.

Sillar, B., 1998. Dung by preference: the choice of fuel as an example of how Andean pottery production is embedded within wider technical, social, and economic practices. *Archaeometry*, **42**(1), 43–60.

Sillar, B., and Tite, M. S., 2000. The challenge of 'technological choices' for materials science approaches in archaeology. *Archaeometry*, **42**(1), 2–20.

Stiner, M. C., Buitenhuis, H., Duru, G., Kuhn, S. L., Mentzer, S. M., Munroe, N. D., Pöllath, N., Quade, J., Tsartsidou, G., and Özbaşaran, M., 2014. A forager–herder trade-off, from broad-spectrum hunting to sheep management at Aşıklı Höyük, Turkey. *Proceedings of the National Academy of Sciences*, **111**(23), 8404–8409.

Stone, E. C., 2013. The organisation of a Sumerian town: the physical remains of ancient social systems. In Crawford, H. E. W. (ed.), *The Sumerian World*. London: Routledge Press, pp. 156–178.

Stoops, G., 2003. *Guidelines for Analysis and Description of Soil and Regolith Thin Sections*. Madison: Soil Science Society of America.

Trümpler, C., and Gerster, G., 2005. *The Past From Above: Aerial Photographs of Archaeological Sites*. Los Angeles: The J. Paul Getty Museum.

Tsartsidou, G., Lev-Yadun, S., Efstratiou, N., and Weiner, S., 2008. Ethnoarchaeological study of phytolith assemblages from an agro-pastoral village in Northern Greece (Sarakini): development and application of a Phytolith Difference Index. *Journal of Archaeological Science*, **35**(3), 600–613.

Tsartsidou, G., Lev-Yadun, S., Efstratiou, N., and Weiner, S., 2009. Use of space in a Neolithic village in Greece (Makri): phytolith analysis and comparison of phytolith assemblages from an ethnographic setting in the same area. *Journal of Archaeological Science*, **36**(10), 2342–2352.

Tung, B., 2005. A preliminary investigation of the mudbrick in Çatalhöyük. In Hodder, I. (ed.), *Changing Materialities at Catalhoyuk: Reports from the 1995–1999 Seasons*. Cambridge: McDonald Institute for Archaeological Research. British Institute for Archaeology at Ankara Monograph 39. Çatalhöyük Research Project, Vol. 5, pp. 215–220. London: British Institute of Archaeology at Ankara.

Ur, J. A., de Jong, L., Giraud, J., Osborne, J. F., and MacGinnis, J., 2013. Ancient cities and landscapes in the Kurdistan region of Iraq: the Erbil plain archaeological survey 2012 season. *Iraq*, **75**, 89–118.

Van der Veen, M., 2007. Formation processes of desiccated and carbonized plant remains – the identification of routine practice. *Journal of Archaeological Science*, **34**(6), 968–990.

Vyncke, K., Degryse, P., Vassilieva, E., and Waelkens, M., 2011. Identifying domestic functional areas. Chemical analysis of floor sediments at the Classical-Hellenistic settlement at Düzen Tepe (SW Turkey). *Journal of Archaeological Science*, **38**(9), 2274–2292.

Walker, G. C., Bowen, J. W., Matthews, W., Roychowdhury, S., Labaune, J., Mourou, G., Menu, M., Hodder, I., and Jackson, J. B., 2013. Sub-surface terahertz imaging through uneven

surfaces: visualizing neolithic wall paintings in Çatalhöyük. *Optics Express*, **21**(7), 8126–8134.
Weiner, S., 2010. *Microarchaeology: Beyond the Visible Archaeological Record*. Cambridge: Cambridge University Press.
Weiss, H., Manning, S. W., Ristvet, L., Mori, L., Besonen, M., McCarthy, A., Quenet, P., Smith, A., and Bahrani, Z., 2012. Tell Leilan Akkadian imperialization, collapse and short-lived reoccupation defined by high-resolution radiocarbon dating. In Weiss, H. (ed.), *Seven Generations since the Fall of Akkad*. Wiesbaden: Harrassowitz. Studia Chaburensia 3, pp. 163–192.
Wilkinson, T. J., 2003. *Archaeological Landscapes of the Near East*. Tucson: University of Arizona Press.
Wilkinson, T. J., French, C., Ur, J. A., and Semple, M., 2010. The geoarchaeology of route systems in northern Syria. *Geoarchaeology*, **25**(6), 745–771.
Wilkinson, T. J., Galiatsatos, N., Lawrence, D., Ricci, A., Dunford, R., and Graham, P., 2012. Late Chalcolithic and Early Bronze Age landscapes of settlement and mobility in the middle Euphrates: a reassessment. *Levant*, **44**(2), 139–185.
Wilson, C. A., Davidson, D. A., and Cresser, M. S., 2009. An evaluation of the site specificity of soil elemental signatures for identifying and interpreting former functional areas. *Journal of Archaeological Science*, **36**(10), 2327–2334.
Zeder, M. A., 2009. The neolithic macro-(r)evolution: macroevolutionary theory and the study of culture change. *Journal of Archaeological Research*, **17**(1), 1–63.

Cross-references

Built Environment
Çatalhöyük
Harappa
Hearths and Combustion Features
Soil Micromorphology
Tombs

TEPHROCHRONOLOGY

Christine Lane and Jamie Woodward
Geography, School of Environment, Education and Development, The University of Manchester, Manchester, UK

Definitions

Tephra: Unconsolidated pyroclastic material explosively ejected during a volcanic eruption. Tephra includes blocks (>32 mm), lapilli (4–32 mm), and ash (<4 mm). Tephra was often called tuff in the early archaeological literature.

Volcanic ash: The finest and most voluminous tephra fraction composed mostly of shards of glass formed by the rapid cooling and explosive breakup of magma during an eruption.

Tephrochronology: The dating of sequences according to the age of layers of tephra preserved within.

Tephrostratigraphy: The use of volcanic ash layers as relative dating horizons. Tephra layers from a single eruption event can be used to correlate sequences precisely that may be some distance apart.

Cryptotephra: Tephra within a sequence that is not visible to the naked eye and may be detected only using instrumental core scanning techniques or by laboratory processing of sediments.

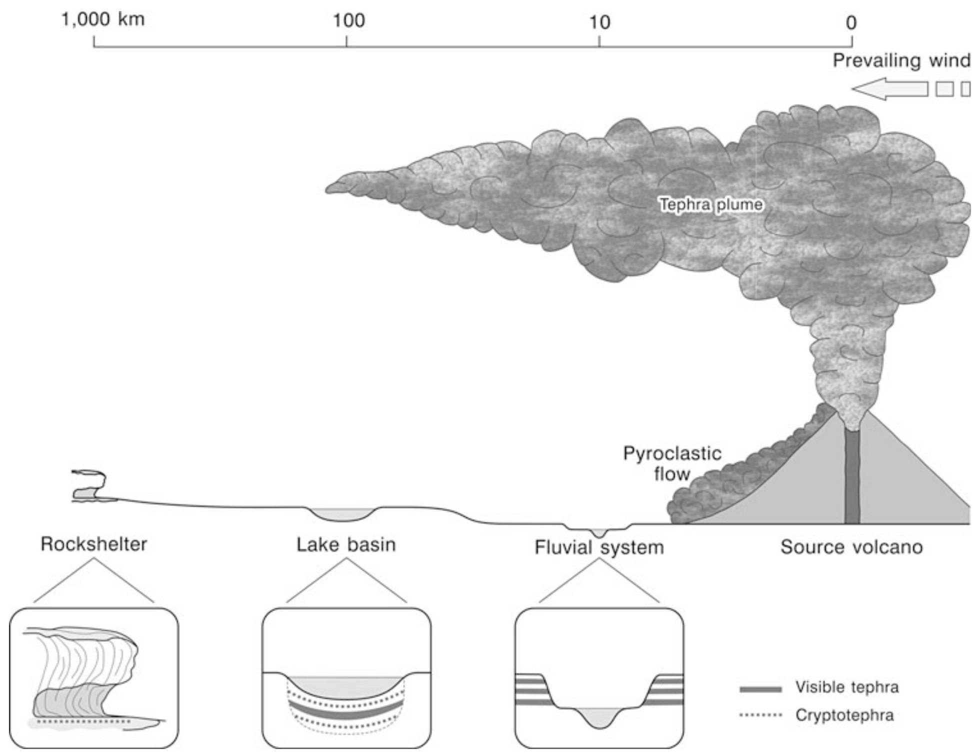
Introduction

Tephra is the debris ejected into the atmosphere during explosive volcanic eruptions. The term was first coined by the Icelandic volcanologist, Thorarinsson (1954), from the Greek for ash (τέφρα). Tephra in fact includes particles that vary greatly in size, density, shape, and chemical makeup, but all varieties can be deposited within archaeological contexts. The largest particles may be blasted to a considerable height, but they typically travel short distances and fall on or close to the volcano itself. The fine-grained ash can be transported much greater distances and deposited in a range of terrestrial and aquatic settings; it is this *distal* tephra that has been the focus of much geoarchaeological research (Figure 1). Even though explosive volcanic eruptions are short-lived, distal tephra can be distributed over a very wide area if atmospheric conditions are favorable. In most cases, a tephra has a distinctive chemistry that allows it to be traced to the source eruption. Tephra layers can therefore assume considerable stratigraphical significance even many hundreds of kilometers from the source volcano because they demonstrate contemporaneity. A selection of archaeological contexts of various ages where distal tephra deposits have been used to refine the dating and establish regional correlations is shown in Table 1. More locally, tephra layers have been used to correlate stratigraphic units across excavation trenches within a single site (Farrand, 2000).

Dating a tephra layer

Tephra can be dated either directly or indirectly by determining the age of material believed to be contemporaneous with tephra deposition (Table 2). The most common direct dating method is $^{40}Ar/^{39}Ar$, which dates the formation of K-rich crystals within a tephra unit. Due to aeolian sorting, these crystals can usually be found in sufficient abundance only in deposits close to the volcanic center. It is therefore essential that the correlation of distal tephra layers to the dated proximal counterparts (i.e., the right volcano and the right eruption) is secure. Where K-rich crystals are not present, indirect dating methods (Table 2) must be used to date a tephra. It is important to establish the relationship between the actual event being dated and the deposition of the tephra layer.

A combination of multiple lines of evidence via a statistical age modeling approach often provides the most precise and accurate age estimate for a tephra layer. Since the early 1990s, Bayesian modeling has been used to combine age information for tephra layers from multiple sites and/or multiple dating approaches (Buck et al., 2003; Blockley et al., 2008), vastly improving the precision with which tephra layers can be dated.



Tephrochronology, Figure 1 A schematic illustration of distal tephra dispersal and deposition in a Quaternary landscape downwind of a volcanic center where three major explosive eruptions have taken place. Three tephra layers have been preserved in the alluvial sediments of the valley floor approximately 10 km downwind of the volcano. About 100 km away, the sedimentary record in the lake basin preserves a faithful record of the two largest eruptions with one visible tephra and two cryptotephra. The rock-shelter sediment record lies at the limits of tephra dispersal and contains a single cryptotephra.

Fingerprinting an eruption

The underlying premise of tephrochronology is that every eruption can be recognized by the chemical composition of the erupted material. Tephra composition is controlled by the chemistry of the magma source region, the path and time taken for the melt to reach the surface, and the dynamics of the eruption. Upon eruption into the cold atmosphere, magma cools and solidifies very rapidly into glass. It is the composition of this glass that is used to fingerprint the tephra, and this can be done in a number of ways. It is now widely recognized that single-grain analyses are preferable for tephra characterization, as these allow the glass and mineral phases to be targeted in isolation. They may also detect any compositional variability within the tephra, which can occur if eruptions are prolonged or if they involve more than one magma body (Smith et al., 2005). Major and minor element compositions are best analyzed using wavelength dispersive spectroscopy on an electron microprobe (WDS-EMP). Typically, SiO_2, TiO_2, Al_2O_3, FeO, MnO, MgO, CaO, Na_2O, K_2O, and P_2O_5 are measured, sometimes with Cl and S, although the latter are present only in trace amounts. Kuehn et al. (2011) provide a detailed discussion of WDS-EMP analyses of volcanic glass.

For many tephra, major and minor element analyses will be sufficient to characterize the eruption. However, multiple eruptions from the same volcano, or different volcanoes in similar settings, may generate tephra with very similar glass compositions. It is therefore useful to measure trace element compositions also using either secondary ion mass spectrometry (SIMS) (Clift and Blusztajn, 1999; Albert et al., 2015) or laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) (Pearce et al., 2007; Tomlinson et al., 2010). In only a few cases, even trace element analyses cannot easily distinguish between multiple eruptions from the same source, for example, the ca. 75 ka Youngest Toba Tuff (Table 1) (Smith et al., 2011; Lane et al., 2012). In such instances, tephra glass shard chemistry is supplemented by mineral analyses.

Cryptotephra

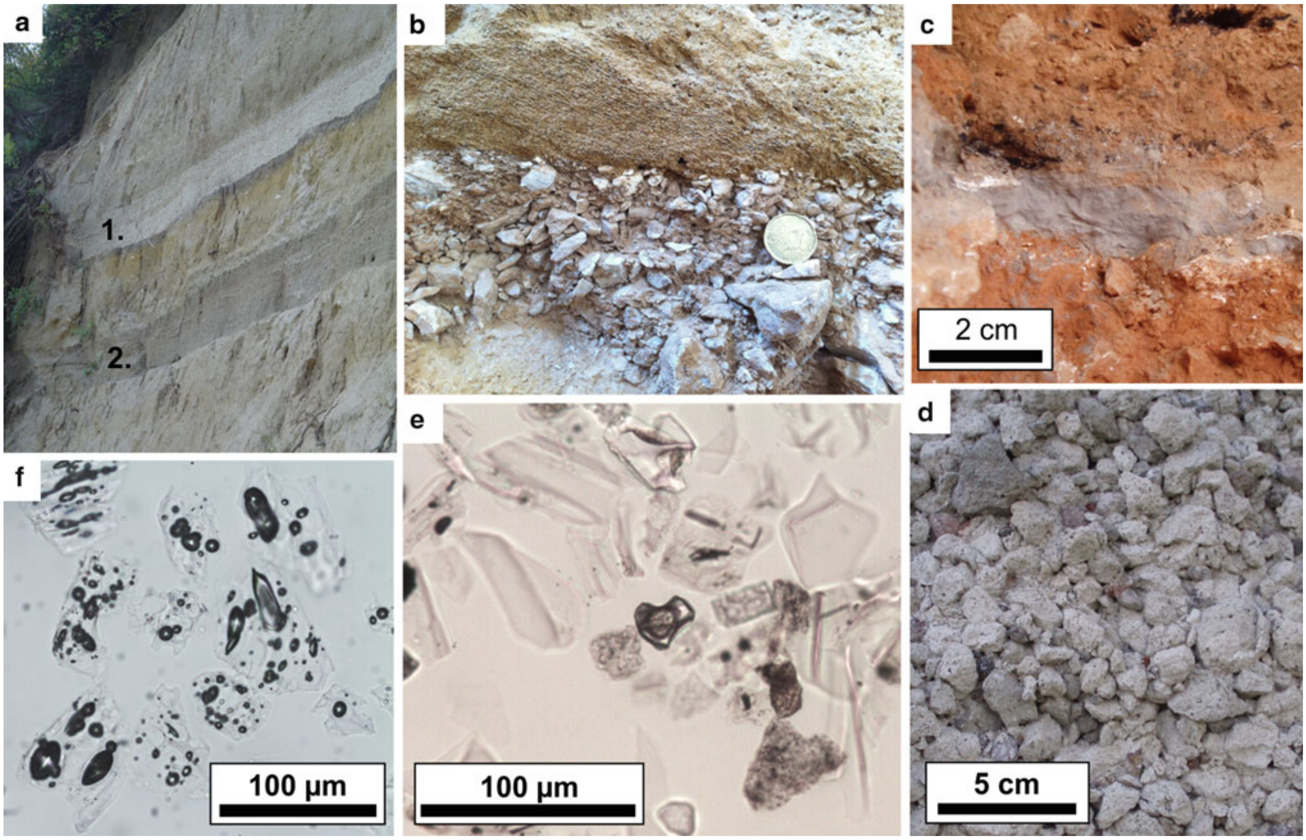
A significant development in tephrochronology, which has led to increased application of the method outside of volcanic regions, has been the detection of cryptotephra layers (Dugmore, 1989; Turney et al., 1997; Davies et al., 2002). Cryptotephra are tephra layers that cannot be detected by the naked eye (Lowe and Hunt, 2001). This

Tephrochronology, Table 1 Notable Quaternary tephra layers that have been widely used as a stratigraphic marker in archaeological research

Time period	Tephra, age, and source	Archaeological context	Dating methods and depositional context	References
Early Pleistocene	Tephra layers in the Konso Formation, ca. 1.90–1.33 Ma, Ethiopian Rift complex	Lower Paleolithic hominin sites in the Rift Valley of East Africa	$^{40}Ar/^{39}Ar$ and correlation within regional marine records	Katoh et al. (2000) and WoldeGabriel et al. (2005)
Middle Pleistocene	Tephra layers in the bedded tuff formation, ca. 235 ka (upper units). Tugen Hills, Kenya Rift Valley	Acheulian to Middle Stone Age transition in East Africa	$^{40}Ar/^{39}Ar$ dating of tephra layers and lavas in the Kapthurin formation	Deino and McBrearty (2002) and Tryon and McBrearty (2006)
Late Pleistocene	Youngest Toba Tuff, ca. 75 ka, Mt. Toba, Sumatra, Indonesia	Middle Paleolithic sites across India	$^{40}Ar/^{39}Ar$ dating of crystals and glass in proximal and distal tephra units	Petraglia et al. (2007), Storey et al. (2012), and Mark et al. (2014)
Late Pleistocene	Campanian Ignimbrite (Y5), ca. 39 ka, Campi Flegrei, southern Italy (Figure 2e)	Middle to Upper Paleolithic cave, rock-shelter, and open-air sites in Europe, South Russia, and North Africa (Figure 2b)	$^{40}Ar/^{39}Ar$, radiocarbon dating, and correlation within marine and lake sediment records	Vitaliano et al. (1981), Pyle et al. (2006), Morley and Woodward (2011), Lowe et al. (2012), and Douka et al. (2014)
Late Glacial	Laacher See tephra, ca. 12.9 ka, East Eifel Volcanic Zone, Germany (Figure 2f)	Final Paleolithic, open-air hunter- gatherer sites and faunal deposits, in western Germany	Age established from annually layered lake sediments and radiocarbon dating	Brauer et al. (1999), Baales et al. (2002), and Riede (2008)
Late Holocene	Thera eruption, ca. 1600 BC, Santorini, Hellenic Arc	Late Bronze Age Minoan civilization, related to destruction of Akrotiri, Greece	Radiocarbon dating of wood within pumice and Bayesian age-model synthesis of dates	Friedrich et al. (2006) and Manning et al. (2006)

Tephrochronology, Table 2 Summary and examples of direct and indirect methods commonly used for dating tephra layers

Method	Description	Material dated	Age range	Example
Direct dating methods				
$^{40}K/^{40}Ar$; $^{40}Ar/^{39}Ar$	Measurement of radiometric decay over time of ^{40}K and daughter product ^{40}Ar	K-rich crystals within tephra deposits or lava flows	^{40}K has a long half-life restricting $^{40}K/^{40}Ar$ to older samples (>100 ka) $^{40}Ar/^{39}Ar$ can date samples as young as Holocene	Dating the Middle Stone Age in East Africa (Morgan and Renne, 2008)
Fission track dating; isothermal plateau fission-track dating	Measurement of tracks accumulated over time by the spontaneous fission of ^{238}U in crystals	Zircon crystals and U-rich glasses in tephra deposits	Dependent on U-content. Typically >50 ka before present	Dating Early-Middle Pleistocene tephra from New Zealand (Shane et al., 1996)
Indirect dating methods				
Radiocarbon	Measurement of radioactive decay of ^{14}C, which is produced in the upper atmosphere and incorporated into all living matter	Organic material immediately below, or within, a tephra unit	A short half-life (~5.7 ka), instrumental detection limits and uncertainties in calibration restrict dating to <50 ka before present	Bronze Age Thera eruption (Friedrich et al., 2006); dating the Campanian Ignimbrite in Kostenki (Douka et al., 2010)
Annual layers	Counting of annual layers formed by seasonal processes in lake sediments and ice core records	Individual layer of sediment or ice containing tephra	Controlled by the length of the record, e.g., layers in the Greenland ice cores can be counted >100 ka	Ice core ages for Vedde and Saksunavatn tephras (Rasmussen et al., 2006) Dating of the Laacher See tephra in laminated lake Meerfelder (Brauer et al., 1999)
Age modeling	Statistical combination of age estimates from a stratigraphic sequence, a number of sites, or different dating methods	Generates a modeled age for the tephra layer	Unlimited	Kaharoa tephra, from New Zealand (Buck et al., 2003), Cape Riva tephra from Santorini (Lee et al., 2013)



Tephrochronology, Figure 2 Images of tephra in the field and under the microscope. **a** Quarry section near Naples, Italy, containing two tephra fall layers: (1) the Mercato tephra from Mt. Vesuvius (~40 cm thick) and (2) the Pomici Principali tephra from Campi Flegrei (~50 cm thick). **b** The Campanian Ignimbrite tephra overlying coarse limestone clasts in the Late Pleistocene sedimentary record of Crvena Stijena rock-shelter in Montenegro. Middle Paleolithic stone tools are found in the deposits below this tephra but not in the deposits above (Morley and Woodward, 2011). **c** The ~17 ka Biancavilla tephra from Mt. Etna is clearly seen as a gray ashfall layer in the sediments of the Haua Fteah rock-shelter in Libya, providing a useful dating horizon for the Epipaleolithic at the site (Douka et al., 2014) (Photo: Robyn Inglis). **d** Example of ash and lapilli size airfall tephra from Gölcük, SW Turkey. **e** Glass shards from the Campanian Ignimbrite tephra seen under the microscope are clear and platelike. This example is taken from the Haua Fteah, Libya. **f** Glass shards from the Laacher See tephra are characterized by lots of gas bubbles (vesicles) trapped within the rapidly cooled magma during the eruption.

is due to their smaller shard sizes, low concentrations, or dilution within the host sediment. Cryptotephra may be found much farther from the volcanic source than equivalent visible tephra units, significantly extending the area over which these isochrons can be utilized (Figure 1). Typically, glass shards (Figure 2e–f) will be the only constituent of cryptotephra deposits, so characterization is carried out in the same way as for visible tephra using EMP and LA-ICP-MS.

Cryptotephra can be detected in a number of ways. Instrumental methods applied to sediment cores, such as magnetic susceptibility and XRF scanning, are effective at detecting layers of relatively high concentration or that are compositionally very different from their host sediment (Gehrels et al., 2008; Kylander et al., 2012). The most reliable way of detecting cryptotephra is by laboratory processing of samples that span the entire sediment record, following a now well-established heavy liquid extraction method (Turney, 1998; Blockley et al., 2005). This method circumvents the need for any chemical treatment of the sediments, which risks chemical alteration and/or dissolution of the glass shards (Pollard et al., 2003; Blockley et al., 2005).

The growth in cryptotephra studies has seen the technique applied widely in dating and correlating Quaternary paleoenvironmental archives from marine and terrestrial environments over continental distances (Turney et al., 2004). Applications in archaeology have been concentrated in Holocene wetland environments where human occupation is closely tied to landscape development and environmental change (Dugmore, 1991; Plunkett, 2009). It is only very recently that this approach has been extended into a wider range of archaeological settings, from open-air sites (Housley et al., 2012) to caves and rock-shelters (Lowe et al., 2012; Douka et al., 2014). Tephra from the 39 ka Campanian Ignimbrite (CI) super-eruption (Figure 2b, e) has been found in multiple cave and rock-shelter sites around the central and Eastern Mediterranean. For example, it is present in Crvena Stijena rock-shelter in Montenegro as a distinctive ~10 cm-thick layer forming the boundary between the Upper and Middle Paleolithic assemblages (Morley and Woodward, 2011). Much farther from the volcanic source, at the Haua Fteah cave in northeastern Libya, it is present as a cryptotephra (Douka et al., 2014). The 39 ka Campanian Ignimbrite tephra is even visible in Late Pleistocene alluvial deposits in southwestern Russia (Table 1). The CI tephra is widely used as a marker layer to correlate Middle to Upper Paleolithic sequences because it provides a precise age estimate that has helped to constrain the timing of this important transition (Pyle et al., 2006; Lowe et al., 2012). Caves and rock-shelters are often complex sedimentary environments (Bailey and Woodward, 1997), so there is a need for careful consideration of the taphonomy of cryptotephra layers, which are unlikely to have entered the site exclusively as direct fallout from the volcanic ash plume (Morley and Woodward, 2011). The development of this approach and the challenges of using cryptotephra to aid the dating and correlation of a wide range of archaeological sites over extended time periods are discussed in Lane et al. (2014).

Summary

The recording of tephra deposits in archaeological contexts is almost as old as the discipline of archaeology itself. A good deal of the classic work on early hominin fossils and Lower Paleolithic stone tools in East Africa is founded upon chronologies derived from the dating of volcanic ash (e.g., Sarna-Wojcicki et al., 1985; WoldeGabriel et al., 2005). Recent developments in the detection and dating of fine distal tephra have substantially enhanced its value as a chronological marker and tool for the correlation of sites. The study of distal tephra is a rapidly growing component of geoarchaeology.

Bibliography

Albert, P. G., Hardiman, M., Keller, J., Tomlinson, E. L., Smith, V. C., Bourne, A. J., Wulf, S., Zanchetta, G., Sulpizio, R., Müller, U. C., Pross, J., Ottolini, L., Matthews, I. P., Blockley, S. P. E., and Menzies, M. A., 2015. Revisiting the Y-3 tephrostratigraphic marker: a new diagnostic glass geochemistry, age estimate, and details on its climatostratigraphical context. *Quaternary Science Reviews*, **118**, 105–121.

Baales, M., Jöris, O., Street, M., Bittmann, F., Weninger, B., and Wiethold, J., 2002. Impact of the Late Glacial eruption of the Laacher See Volcano, Central Rhineland, Germany. *Quaternary Research*, **53**(3), 273–288.

Bailey, G. N., and Woodward, J. C., 1997. The Klithi deposits: sedimentology, stratigraphy and chronology. In Bailey, G. N. (ed.), *Klithi: Palaeolithic Settlement and Quaternary Landscapes in Northwest Greece*. Cambridge: McDonald Institute for Archaeological Research. Excavation and Intra-Site Analysis at Klithi, Vol. 1, pp. 61–94.

Blockley, S. P. E., Pyne-O'Donnell, S. D. F., Lowe, J. J., Matthews, I. P., Stone, A., Pollard, A. M., Turney, C. S. M., and Molyneux, E. G., 2005. A new and less destructive laboratory procedure for the physical separation of distal glass tephra shards from sediments. *Quaternary Science Reviews*, **24**(16–17), 1952–1960.

Blockley, S. P. E., Bronk Ramsey, C., and Pyle, D. M., 2008. Improved age modelling and high-precision age estimates of late Quaternary tephras, for accurate palaeoclimate reconstruction. *Journal of Volcanology and Geothermal Research*, **177**(1), 251–262.

Brauer, A., Endres, C., and Negendank, J. F. W., 1999. Lateglacial calendar year chronology based on annually laminated sediments from Lake Meerfelder Maar, Germany. *Quaternary International*, **61**(1), 17–25.

Buck, C. E., Higham, T. F. G., and Lowe, D. J., 2003. Bayesian tools for tephrochronology. *The Holocene*, **13**(5), 639–647.

Clift, P., and Blusztajn, J., 1999. The trace-element characteristics of Aegean and Aeolian volcanic arc marine tephra. *Journal of Volcanology and Geothermal Research*, **92**(3–4), 321–347.

Davies, S. M., Branch, N. P., Lowe, J. J., and Turney, C. S. M., 2002. Towards a European tephrochronological framework for termination 1 and the early Holocene. *Philosophical Transactions of the Royal Society: Mathematical Physical and Engineering Sciences A*, **360**(1793), 767–802.

Deino, A. L., and McBrearty, S., 2002. $^{40}Ar/^{39}Ar$ dating of the Kapthurin Formation, Baringo, Kenya. *Journal of Human Evolution*, **42**(1–2), 185–210.

Douka, K., Higham, T., and Sinitsyn, A., 2010. The influence of pretreatment chemistry on the radiocarbon dating of Campanian Ignimbrite-aged charcoal from Kostenki 14 (Russia). *Quaternary Research*, **73**(3), 583–587.

Douka, K., Jacobs, Z., Lane, C., Grün, R., Farr, L., Hunt, C., Inglis, R. H., Reynolds, T., Albert, P., Aubert, M., Cullen, V., Hill, E., Kinsley, L., Roberts, R. G., Tomlinson, E. L., Wulf, S., and Barker, G., 2014. The chronostratigraphy of the Haua Fteah cave (Cyrenaica, northeast Libya). *Journal of Human Evolution*, **66**, 39–63.

Dugmore, A., 1989. Icelandic volcanic ash in Scotland. *Scottish Geographical Magazine*, **105**(3), 168–172.

Dugmore, A. J., 1991. Tephrochronology and UK archaeology. In Budd, P., Chapman, C., Jackson, C., Janaway, R., and Ottoway, B. (eds.), *Archaeological Science: Proceedings of a Conference on the Application of Scientific Techniques to Archaeology, Bradford, September 1989*. Oxford: Oxbow Books. Oxbow Monograph, Vol. 9, pp. 242–250.

Farrand, W. R., 2000. *Depositional History of Franchthi Cave: Stratigraphy, Sedimentology, and Chronology*. Bloomington: Indiana University Press. Excavations at Franchthi Cave, Greece, fasc. 12.

Friedrich, W. L., Kromer, B., Friedrich, M., Heinemeier, J., Pfeiffer, T., and Talamo, S., 2006. Santorini eruption radiocarbon dated to 1627–1600 BC. *Science*, **312**(5773), 548.

Gehrels, M. J., Newnham, R. M., Lowe, D. J., Wynne, S., Hazell, Z. J., and Caseldine, C., 2008. Towards rapid assay of cryptotephra in peat cores: review and evaluation of various methods. *Quaternary International*, **178**(1), 68–84.

Housley, R. A., Lane, C. S., Cullen, V. L., Weber, M.-J., Riede, F., Gamble, C. S., and Brock, F., 2012. Icelandic volcanic ash from the Late-glacial open-air archaeological site of Ahrenshöft LA 58 D, North Germany. *Journal of Archaeological Science*, **39**(3), 708–716.

Katoh, S., Nagaoka, S., WoldeGabriel, G., Renne, P., Snow, M. G., Beyene, Y., and Suwa, G., 2000. Chronostratigraphy and correlation of the Plio-Pleistocene tephra layers of the Konso Formation, southern Main Ethiopian Rift, Ethiopia. *Quaternary Science Reviews*, **19**(13), 1305–1317.

Kuehn, S. C., Froese, D. G., and Shane, P. A. R., 2011. The INTAV intercomparison of electron-beam microanalysis of glass by tephrochronology laboratories: results and recommendations. *Quaternary International*, **246**(1–2), 19–47.

Kylander, M. E., Lind, E. M., Wastegård, S., and Löwemark, L., 2012. Recommendations for using XRF core scanning as a tool in tephrochronology. *The Holocene*, **22**(3), 371–375.

Lane, C. S., Blockley, S. P. E., Mangerud, J., Smith, V. C., Lohne, Ø. S., Tomlinson, E. L., Matthews, I. P., and Lotter, A. F., 2012. Was the 12.1 ka Icelandic Vedde Ash one of a kind? *Quaternary Science Reviews*, **33**, 87–99.

Lane, C. S., Cullen, V. L., White, D., Bramham-Law, C. W. F., and Smith, V. C., 2014. Cryptotephra as a dating and correlation tool in archaeology. *Journal of Archaeological Science*, **42**, 42–50.

Lee, S., Bronk Ramsey, C., and Hardiman, M., 2013. Modeling the age of the Cape Riva (Y-2) tephra. *Radiocarbon*, **55**(2–3), 741–747.

Lowe, D. J., and Hunt, J. B., 2001. A summary of terminology used in tephra-related studies. In Juvigné, E. H., and Raynal, J.-P. (eds.), *Tephras: chronologie, archéologie: actes du colloque, à Brives-Charensac (Haute-Loire), du 28 au 29 août 1998*. Goudet: Centre de documentation et de recherches archéologiques départemental d'Auvergne. Les Dossiers de l'Archéo-Logis, Vol. 1, pp. 17–22.

Lowe, J., Barton, N., Blockley, S., Bronk Ramsey, C., Cullen, V. L., Davies, W., Gamble, C., Grant, K., Hardiman, M., Housley, R., Lane, C. S., Lee, S., Lewis, M., MacLeod, A., Menzies, M., Müller, W., Pollard, M., Price, C., Roberts, A. P., Rohling, E. J., Satow, C., Smith, V. C., Stringer, C. B., Tomlinson, E. L., White, D., Albert, P., Arienzo, I., Barker, G., Borić, D., Carandente, A., Civetta, L., Ferrier, C., Guadelli, J.-L., Karkanas, P., Koumouzelis, M., Müller, U. C., Orsi, G., Pross, J., Rosi, M., Shalamanov-Korobar, L., Sirakov, N., and Tzedakis, P. C., 2012. Volcanic ash layers illuminate the resilience of Neanderthals and early modern humans to natural hazards. *Proceedings of the National Academy of Sciences*, **109**(34), 13532–13537.

Manning, S. W., Bronk Ramsey, C., Kutschera, W., Higham, T., Kromer, B., Steier, P., and Wild, E. M., 2006. Chronology for the Aegean Late Bronze Age 1700–1400 B.C. *Science*, **312**(5773), 565–569.

Mark, D. F., Petraglia, M., Smith, V. C., Morgan, L. E., Barfod, D. N., Ellis, B. S., Pearce, N. J., Pal, J. N., and Korisettar, R., 2014. A high-precision $^{40}Ar/^{39}Ar$ age for the Young Toba Tuff and dating of ultra-distal tephra: forcing of quaternary climate and implications for hominin occupation of India. *Quaternary Geochronology*, **21**, 90–103.

Morgan, L. E., and Renne, P. R., 2008. Diachronous dawn of Africa's Middle Stone Age: new $^{40}Ar/^{39}Ar$ ages from the Ethiopian Rift. *Geology*, **36**(12), 967–970.

Morley, M. W., and Woodward, J. C., 2011. The Campanian Ignimbrite (Y5) tephra at Crvena Stijena Rockshelter, Montenegro. *Quaternary Research*, **75**(3), 683–696.

Pearce, N. J. G., Denton, J. S., Perkins, W. T., Westgate, J. A., and Alloway, B. V., 2007. Correlation and characterisation of individual glass shards from tephra deposits using trace element laser ablation ICP-MS analyses: current status and future potential. *Journal of Quaternary Science*, **22**(7), 721–736.

Petraglia, M., Korisettar, R., Boivin, N., Clarkson, C., Ditchfield, P., Jones, S., Koshy, J., Lahr, M. M., Oppenheimer, C., Pyle, D., Roberts, R., Schwenninger, J.-L., Arnold, L., and White, K., 2007. Middle Paleolithic assemblages from the Indian subcontinent before and after the Toba super-eruption. *Science*, **317**(5834), 114–116.

Plunkett, G., 2009. Land-use patterns and cultural change in the Middle to Late Bronze Age in Ireland: inferences from pollen records. *Vegetation History and Archaeobotany*, **18**(4), 273–295.

Pollard, A. M., Blockley, S. P. E., and Ward, K. R., 2003. Chemical alteration of tephra in the depositional environment: theoretical stability modelling. *Journal of Quaternary Science*, **18**(5), 385–394.

Pyle, D. M., Ricketts, G. D., Margari, V., van Andel, T. H., Sinitsyn, A. A., Praslov, N. D., and Lisitsyn, S., 2006. Wide dispersal and deposition of distal tephra during the Pleistocene 'Campanian Ignimbrite/Y5' eruption, Italy. *Quaternary Science Reviews*, **25** (21–22), 2713–2728.

Rasmussen, S. O., Andersen, K. K., Svensson, A. M., Steffensen, J. P., Vinther, B. M., Clausen, H. B., Siggaard-Andersen, M.-L., Johnsen, S. J., Larsen, L. B., Dahl-Jensen, D., Bigler, M., Röthlisberger, R., Fischer, H., Goto-Azuma, K., Hansson, M. E., and Ruth, U., 2006. A new Greenland ice core chronology for the last glacial termination. *Journal of Geophysical Research, D: Atmospheres*, **111**(D6), D06102.

Riede, F., 2008. The Laacher See-eruption (12,920 BP) and material culture change at the end of the Allerød in Northern Europe. *Journal of Archaeological Science*, **35**(3), 591–599.

Sarna-Wojcicki, A. M., Meyer, C. E., Roth, P. H., and Brown, F. H., 1985. Ages of tuff beds at East African early hominid sites and sediments in the Gulf of Aden. *Nature*, **313**(6000), 306–308.

Shane, P., Alloway, B., Black, T., and Westgate, J., 1996. Isothermal plateau fission-track ages of tephra beds in an early-middle Pleistocene marine and terrestrial sequence, Cape Kidnappers, New Zealand. *Quaternary International*, **34–36**, 49–53.

Smith, V. C., Shane, P., and Nairn, I. A., 2005. Trends in rhyolite geochemistry, mineralogy, and magma storage during the last 50 kyr at Okataina and Taupo volcanic centres, Taupo Volcanic Zone, New Zealand. *Journal of Volcanology and Geothermal Research*, **148**(3–4), 372–406.

Smith, V. C., Pearce, N. J. G., Matthews, N. E., Westgate, J. A., Petraglia, M. D., Haslam, M., Lane, C. S., Korisettar, R., and Pal, J. N., 2011. Geochemical fingerprinting of the widespread Toba tephra using biotite compositions. *Quaternary International*, **246**(1–2), 97–104.

Storey, M., Roberts, R. G., and Saidin, M., 2012. Astronomically calibrated $^{40}Ar/^{39}Ar$ age for the Toba supereruption and global synchronization of late Quaternary records. *Proceedings of the National Academy of Sciences*, **109**(46), 18684–18688.

Thorarinsson, S., 1954. The tephra-fall from Hekla on March 29th 1947. In Einarsson, T., Kjartansson, G., and Thorarinsson, S. (eds.), *The Eruption of Hekla 1947–48*. Reykjavik: Vísindafélag Íslendinga and the Museum of Natural History, Reykjavík, Vol. 2. no. 3.

Tomlinson, E. L., Thordarson, T., Müller, W., Thirlwall, M., and Menzies, M. A., 2010. Microanalysis of tephra by LA-ICP-MS – strategies, advantages and limitations assessed using the Thorsmörk ignimbrite (Southern Iceland). *Chemical Geology*, **279**(3–4), 73–89.

Tryon, C. A., and McBrearty, S., 2006. Tephrostratigraphy of the Bedded Tuff Member (Kapthurin Formation, Kenya) and the nature of archaeological change in the later Middle Pleistocene. *Quaternary Research*, **65**(3), 492–507.

Turney, C. S. M., 1998. Extraction of rhyolitic component of Vedde microtephra from minerogenic lake sediments. *Journal of Paleolimnology*, **19**(2), 199–206.

Turney, C. S. M., Harkness, D. D., and Lowe, J. J., 1997. The use of microtephra horizons to correlate Late-glacial lake sediment successions in Scotland. *Journal of Quaternary Science*, **12**(6), 525–531.

Turney, C. S. M., Lowe, J. J., Davies, S. M., Hall, V., Lowe, D. J., Wastegård, S., Hoek, W. Z., and Alloway, B., 2004. Tephrochronology of last termination sequences in Europe: a protocol for improved analytical precision and robust correlation procedures (a joint SCOTAV-INTIMATE proposal). *Journal of Quaternary Science*, **19**(2), 111–120.

Vitaliano, C. J., Taylor, S. R., Farrand, W. R., and Jacobsen, T. W., 1981. Tephra layer in Franchthi Cave, Peleponnesos, Greece.

In Self, S., and Sparks, R. S. J. (eds.), *Tephra Studies: Proceedings of the NATO Advanced Study Institute "Tephra Studies as a Tool in Quaternary Research," Held in Laugarvatn and Reykjavík, Iceland, June 18–29, 1980*. Dordrecht: D. Reidel. NATO Advanced Study Institutes, Series C, Mathematical and Physical Sciences, Vol. 75, pp. 373–379.

WoldeGabriel, G., Hart, W. K., Katoh, S., Beyene, Y., and Suwa, G., 2005. Correlation of Plio-Pleistocene tephra in Ethiopian and Kenyan rift basins: temporal calibration of geological features and hominid fossil records. *Journal of Volcanology and Geothermal Research*, **147**(1–2), 81–108.

Cross-references

$^{40}Ar/^{39}Ar$ and K–Ar Geochronology
Cave Settings
Chronostratigraphy
Haua Fteah
Kostenki, Russia
Radiocarbon Dating
Rockshelter Settings
Santorini
Volcanoes and People

TOMBS

Panagiotis Karkanas
Ephoreia of Palaeoanthropology & Speleology
of Southern Greece, Athens, Greece

Synonyms

Burial; Catacomb; Grave; Interment; Mausoleum; Sepulcher; Vault

Definitions

Tomb: Any structurally enclosed interment space or burial chamber.

Introduction

Funerary practices are among the most important elements of social life, and although they focus on the disposition of the dead, they probably tell us more about the living (Bettencourt, 2008). From the simplest pits covered with gravel to the highly elaborate structures of the pyramids in Egypt, tombs provide a wide variety of information about past funerary behavior and its social context. The varied grave goods deposited around the deceased – including jewelry, clothing residues, weapons, tools, cooking equipment, and provisions in association with human skeletal remains – place tombs among the most informative archaeological assemblages for the reconstruction of ancient social structures (Pearson, 2003).

Throughout the world, tombs occur in many forms and incorporate structural aspects that are often unique to each society. These include underground carved-out spaces (cists and chamber tombs) sometimes lined with construction material (tholos tombs or vault tombs), large stone constructions covered by an earthen mound (megalithic tombs), or free-standing, aboveground structures (mausolea and pyramids). Tombs may contain one or more interments of individuals or family groups, or they can encompass large public burials (catacombs). Interments can be inhumations or cremations, and the remains can be enclosed within a container or simply placed on or within the ground. Notwithstanding their importance, however, there have been few geoarchaeological studies of tombs, and most of these have focused on geophysical prospection and provenance.

Geophysical prospection

Several geophysical methods are employed for locating and mapping buried or underground tombs. GPR, or ground-penetrating radar (qv), which is based on the transmission of radio waves to image the subsurface, is usually used because it is rapid and nondestructive. Examples include the detection of underground megalithic tombs in Galicia, Spain (Lorenzo and Arias, 2005), the investigation of a subterranean tomb in Japan (Edwards et al., 2000), and advanced three-dimensional GPR investigations to locate and characterize tombs inside medieval chapels (e.g., Böniger and Tronicke, 2010). More recently, near-surface magnetic investigations have also been used successfully to locate buried tombs and other structures associated with the Amenemhat II pyramid complex in Dahshur, Egypt (Abdallatif et al., 2010).

Provenance studies

Since most types of tombs include stone construction, provenance studies are the most commonly applied geoarchaeological analyses. Geological observations supplemented by petrographic (qv) and geochemical investigations are usually employed to characterize the building materials and identify their source. In particular, provenance studies of marble construction in tombs are based on oxygen isotopic (qv) data and chemistry of fluid inclusions, which are compared with well-known quarry sources of high-quality marble (e.g., Walker, 1984; Miriello et al., 2010; Prochaska and Grillo, 2010).

The construction of megalithic tombs between the fifth and the second millennia BC in Western Europe has been the subject of intensive investigations. Most of the studies have confirmed that the tombs were built from stone that was available within a radius of 5 km from the site (Thorpe and Williams-Thorpe, 1991; Patton, 1992; Vicens et al., 2010). This contrasts with provenance studies conducted at the famous megalithic monument of Stonehenge, where transport over a range of several tens or even hundreds of km has been suggested (Thorpe and Williams-Thorpe, 1991; Williams-Thorpe et al., 2006).

The legendary Egyptian tombs have been the stuff of mystery and imagination, as well as curious interpretations. It has been claimed that the blocks comprising the famous pyramids of Giza were not quarried at all. Davidovits and Morris (1988) advanced an unconventional hypothesis that the blocks were man-made and produced by pouring a mixture of disaggregated limestone and a geopolymeric binder that resulted in a material almost indistinguishable from natural limestone. More recently, this idea was resuscitated by Barsoum et al. (2006), who claimed to have identified artificial microconstituents in some blocks using scanning and transmission electron microscopy (SEM and TEM) (qv). Geological observations have provided undisputable proof that the blocks were quarried, however. The evidence includes ripple laminations, repeated layering, calcite-filled tectonic fractures, as well as numerous sharp cross sections of clams and fragile calcite worm tubes and burrows that were formed during deposition of the rock (Folk and Campbell, 1992). In addition, a variety of mineralogical and chemical instrumental techniques like optical microscopy, XRD (qv), SEM (qv), DTA, ICP (qv), and FTIR (qv) were also used to verify their natural origin (Folk and Campbell, 1992; Ingram et al., 1993).

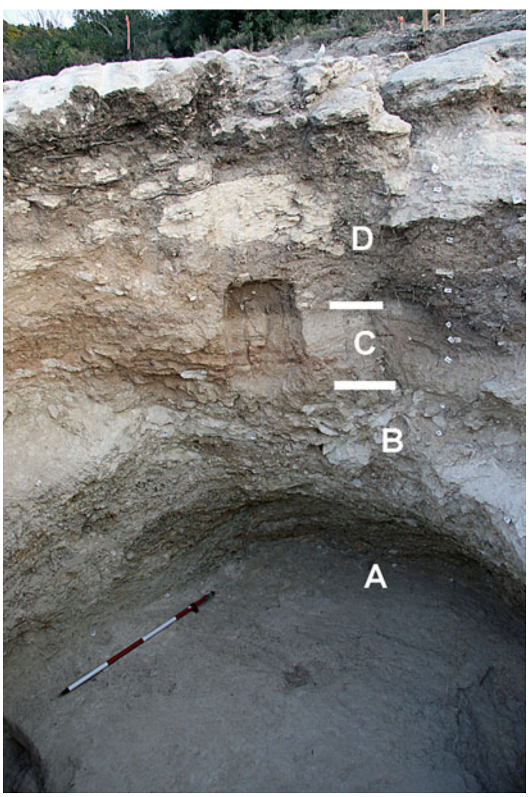
Tombs, Figure 1 Interior of a chamber tomb showing three burial pits that are related to the same floor surface. Ayia Sotira, Nemea, Greece (Photo courtesy of J. Wright and M. Dabney).

Studies of tomb sediments

The word tomb comes from the Greek τύμβος ("tymvos" or sepulchral mound) and has a strong connotation linking it to earthen structures. Indeed, tombs were very often originally covered with an earthen mound, such as with megalithic and chamber tombs. However, only rarely have geoarchaeological approaches been used to decipher the source and processing of soil and sediment for the building of mounds (Cremeens et al., 1997; Cremeens, 2005; Canti, 2009; Villagran et al., 2009; Sherwood and Kidder, 2011) (see *Mounds and Other Earthworks* for details). Rarer still are studies of the tomb sediments themselves. Although some tombs contain very little accumulated interior sediment, in cases where the tombs were repeatedly used, stratified deposition can occur in association with not only their continual opening and closing but also with their maintenance. Tombs are often looted during modern times, but they were also plundered in antiquity. These activities may have created disturbances and sediment build up inside the tomb. Underground tombs often collapse and fill with breakdown material together with sediment and soil from the surrounding area. Such tombs bearing stratified deposits are nevertheless challenging to excavate because their usually narrow, cramped spaces leave little place between the interments in which to work. Since tombs are highly susceptible to robbing (even during their excavation), leaving a standing balk that may contain artifacts raises the theft risk as well as logistical problems of access. By adjusting excavation strategy according to the type of tomb, however, the study of the interior sediment record can elucidate the complex history of use and provide important information on mortuary behaviors. Applying a soil micromorphology (qv) approach in this way, maintenance practices were identified in the form of fine lime plaster floors in the interior of Mycenaean chamber tombs (Karkanas et al., 2012). This investigation allowed the separation of burial groups based on their relationship to floor surfaces (Figure 1). Moreover, questions about the preparation of the area and mode of corpse deposition have also been answered with soil micromorphology. In the Celtic sanctuary of Ribemont-sur-Ancre (Somme, France), it was concluded that a hanging funerary platform had been constructed with mud-brick and mortar where the corpses remained exposed for a considerable time before they fell to the floor (Courty, 2001: Figure 8.13). Cadaver decomposition usually leaves a chemical signature in the soil consisting of iron- and phosphorus-rich compounds (Żychowski, 2011) or elevated manganese concentrations (Keely et al., 1977). Where remains have already decomposed and no visible remains survive, these soil silhouettes of trace chemical residues can enable the detection of preexisting burials (Keely et al., 1977), and they can probably differentiate primary from secondary burials as well.

Of particular interest are the occasional corridors (singular = dromos in Greek) that lead to the main chamber of some tomb types. Such corridors are usually filled with sediment. In the study of some Mycenaean chamber tombs, field sedimentological observations corroborated with soil micromorphology provided details about the process of backfilling and reopening of the corridors of the tombs and the location, number, and slope of these reopenings (Figure 2) (Wright et al., 2008; Karkanas et al., 2012). Also observed was a suite of sedimentary structures attributed to grain flow and debris fall processes associated with the formation of small piles during shoveling of debris in the tomb. The grain flow resulted from the failure of material on the sides of the piles and is

Tombs, Figure 2 Corridor (dromos) of a Mycenaean chamber tomb (Ayia Sotira, Nemea, Greece). Two phases marked by stones representing the wall blocking the main chamber entrance are seen in the balk at the end of the excavated corridor. Along the balk of the right corridor wall, sedimentary features attributed to the reopening and backfilling of the corridor are marked with *arrows*.



Tombs, Figure 3 Stratigraphy of a collapsed chamber tomb. *A* chamber, *B* collapsed roof, *C* finely laminated water-lain sediment, *D* final filling with colluvium and soil debris. Ayia Sotira, Nemea, Greece (Photo courtesy of R. K. A. Smith).

characterized by ubiquitous particle collisions; the debris fall was produced with collapse of the piles and rapid chaotic movement in the form of dry avalanches. Understanding these processes enables features related to reopenings and regular backfilling to be differentiated. In addition, identifying details of the chamber collapse process offered a better understanding of the taphonomy of the burials inside the tombs (Figure 3).

Regional studies

Finally, regional geoarchaeological studies can shed light on the distribution patterns of some types of tomb, revealing important aspects of former societies. A study by Perry and Davidson (1987) has shown that the distribution of Neolithic chambered cairns on the island of Arran (Scotland) depended generally on factors involving the character of the land and occasionally on geomorphic ones. The most important factor appeared to be proximity to agricultural land, and based on this inference, they recognized that the agricultural component of the island's economy increased through time.

Summary

Geoarchaeological studies in tombs have so far confined to their initial assessment, geophysical prospection, and provenance studies of stone construction materials. Only very recently has a geoarchaeological perspective been applied to the study of site formation processes within and around tombs. This perspective can be applied to many types of tombs and promises to reveal important details about mortuary practices.

Bibliography

Abdallatif, T., El Emam, A. E., Suh, M., El Hemaly, I. A., Ghazala, H. H., Ibrahim, E. H., Odah, H. H., and Deebes, H. A., 2010. Discovery of the causeway and the mortuary temple of the pyramid of Amenemhat II using near-surface magnetic investigation, Dahshour, Giza, Egypt. *Geophysical Prospecting*, **58**(2), 307–320.

Barsoum, M. W., Ganguly, A., and Hug, G., 2006. Microstructural evidence of reconstituted limestone blocks in the great pyramids of Egypt. *Journal of the American Ceramic Society*, **89**(12), 3788–3796.

Bettencourt, A. M. S., 2008. Life and death in the Bronze Age of the NW of Iberian Peninsula. In Fahlander, F., and Oestigaard, T. (eds.), *The Materiality of Death: Bodies, Burials, Belief*. Oxford: Archaeopress. BAR International Series, Vol. 1768, pp. 99–104.

Böniger, U., and Tronicke, J., 2010. Improving the interpretability of 3D GPR data using target-specific attributes: application to tomb detection. *Journal of Archaeological Science*, **37**(2), 360–367.

Canti, M. G., 2009. Geoarchaeological studies associated with remedial measures at Silbury Hill, Wiltshire, UK. *Catena*, **78**(3), 301–309.

Courty, M.-A., 2001. Microfacies analysis assisting archaeological stratigraphy. In Goldberg, P., Holliday, V. T., and Ferring, C. R. (eds.), *Earth Sciences and Archaeology*. New York: Kluwer, pp. 205–239.

Cremeens, D. L., 2005. Micromorphology of Cotiga Mound, West Virginia. *Geoarchaeology*, **20**(6), 581–597.

Cremeens, D. L., Landers, D. B., and Frankenberg, S. R., 1997. Geomorphic setting and stratigraphy of Cotiga Mound, Mingo County, West Virginia. *Geoarchaeology*, **12**(5), 459–477.
Davidovits, J., and Morris, M., 1988. *The Pyramids: An Enigma Solved*. New York: Hippocrene.
Edwards, W., Okita, M., and Goodman, D., 2000. Investigation of a subterranean tomb in Miyazaki, Japan. *Archaeological Prospection*, **7**(4), 215–224.
Folk, R. L., and Campbell, D. H., 1992. Are the pyramids of Egypt built of poured concrete blocks? *Journal of Geological Education*, **40**(1), 25–34.
Ingram, K. D., Daugherty, K. E., and Marshall, J. L., 1993. The pyramids—cement or stone. *Journal of Archaeological Science*, **20**(6), 681–687.
Karkanas, P., Dabney, M. K., Smith, R. K. A., and Wright, J. C., 2012. The geoarchaeology of Mycenaean chamber tombs. *Journal of Archaeological Science*, **39**(8), 2722–2732.
Keely, H. C. M., Hudson, G. E., and Evans, J., 1977. Trace element contents of human bones in various states of preservation. 1. The soil silhouette. *Journal of Archaeological Science*, **4**(1), 19–24.
Lorenzo, H., and Arias, P., 2005. A methodology for rapid archaeological site documentation using ground-penetrating radar and terrestrial photogrammetry. *Geoarchaeology*, **20**(5), 521–535.
Miriello, D., Malagodi, M., Ruffolo, S. A., La Russa, M. F., Crisci, G. M., Pezzino, A., Galluccio, R., Barca, D., and Marasco, E., 2010. Diagnostics, deterioration and provenance of stone materials from the Jefferson Page tomb (Non-Catholic Cemetery of Rome, Italy). *Environmental Earth Science*, **60**(4), 829–836.
Patton, M., 1992. Megalithic transport and territorial markers: evidence from the Channel Islands. *Antiquity*, **66**(251), 392–395.
Pearson, M. P., 2003. *The Archaeology of Death and Burial*, 2nd edn. Stroud: Sutton.
Perry, C. M., and Davidson, D. A., 1987. A spatial analysis of Neolithic chambered cairns on the island of Arran, Scotland. *Geoarchaeology*, **2**(2), 121–130.
Prochaska, W., and Grillo, S. M., 2010. A new method for the determination of the provenance of white marbles by chemical analysis of inclusion fluids: the marbles of the mausoleum of Belevi/Turkey. *Archaeometry*, **52**(1), 59–82.
Sherwood, S. C., and Kidder, T. R., 2011. The DaVincis of dirt: geoarchaeological perspectives on Native American mound building in the Mississippi River basin. *Journal of Anthropological Archaeology*, **30**(1), 69–87.
Thorpe, R. S., and Williams-Thorpe, O., 1991. The myth of long-distance megalith transport. *Antiquity*, **65**(246), 64–73.
Vicens, E., Arribas, M. E., Clop, X., Estrada, M. R., Maestro, E., Oms, O., Serrat, D., and Molist, M., 2010. Characterization and provenance of the slabs of the Puigseslloses Megalith, Barcelona, Spain. *Geoarchaeology*, **25**(2), 195–219.
Villagran, X. S., Giannini, P. C. F., and DeBlasis, P., 2009. Archaeofacies analysis: using depositional attributes to identify anthropic processes of deposition in a monumental shell mound of Santa Catarina State, Southern Brazil. *Geoarchaeology*, **24**(3), 311–335.
Walker, S., 1984. Marble origins by isotopic analysis. *World Archaeology*, **16**(2), 204–221.
Williams-Thorpe, O., Jones, M. C., Potts, P. J., and Webb, P. C., 2006. Preseli dolerite bluestones: axe-heads, Stonehenge monoliths and outcrop sources. *Oxford Journal of Archaeology*, **25**(1), 29–46.
Wright, J. C., Pappi, E., Triantaphyllou, S., Dabney, M. K., Karkanas, P., Kotzamani, G., and Livarda, A., 2008. Nemea Valley archaeological project, excavations at Barnavos, final report. *Hesperia*, **77**(4), 607–654.
Żychowski, J., 2011. Geological aspects of decomposition of corpses in mass graves from WW1 and 2, located in SE Poland. *Environmental Earth Sciences*, **64**(2), 437–448.

Cross-references

Fourier Transform Infrared Spectroscopy (FTIR)
Inductively Coupled Plasma-Mass Spectrometry (ICP-MS)
Oxygen Isotopes
Petrography
Scanning Electron Microscopy (SEM)
Soil Micromorphology
X-ray Diffraction (XRD)

TRAMPLING

Christopher E. Miller
Institute for Archaeological Sciences, Senckenberg Centre for Human Evolution and Paleoenvironment, University of Tübingen, Tübingen, Germany

Trampling, also sometimes called scuffage or treadage, refers to the alteration and modification of artifacts and deposits caused by humans or animals walking on a surface. Archaeologists have noted and studied the influence of trampling on artifacts since the 1950s (Bordes and Bourgon, 1951). From that time, researchers have conducted numerous actualistic, laboratory, and ethnoarchaeological studies to investigate the effects of trampling on surface modification of bones, breakage and edge damage of lithics, and vertical and horizontal displacement of artifacts within a deposit. Geoarchaeologists have also conducted studies to investigate the micromorphological effects of trampling on deposits and anthropogenic features.

Zooarchaeologists have looked at the effects of human and animal trampling of bone over a variety of substrates with the goals of distinguishing between cut marks and trampling marks and determining the role that trampling plays in the taphonomy of faunal assemblages. Most of these studies conclude that cut marks exhibit morphological characteristics distinct from trampling marks, which can be difficult to distinguish from sedimentary abrasion caused by other processes such as pedoturbation. Similar studies have been conducted to examine the effects of trampling on damage to lithic artifacts. Some studies noted limited edge damage (Eren et al., 2010), whereas others noted that trampling can cause modifications that mimic the marks of certain tool types (McBrearty et al., 1998). The difference in these results likely reflects variations in the substrates used for the experiments.

Trampling can have significant effects on both the vertical and horizontal distribution of artifacts within a deposit. However, despite numerous studies, researchers report varying or even contradictory results. Some studies note vertical displacement of only 1.5 cm following trampling (Nielsen, 1991), while others report maximum displacement of up to 16 cm (Eren et al., 2010). Similarly, some researchers report horizontal and vertical size sorting and displacement of artifacts by trampling, whereas others do not. The variables that influence these results include (1) the intensity of the trampling, (2) the nature of the substrate, (3) the thickness of the deposits covering the trampled pieces, and (4) the weight, size, and shape of the artifacts (Villa and Courtin, 1983). Of these variables, the type of substrate – and particularly its penetrability – is likely the most significant.

Compaction of the substrate following trampling has been reported from some experiments that also note the presence of in situ crushed and snapped bone, identifiable in micromorphological thin section (Miller et al., 2010). Similarly, Banerjea et al. (2013), in a micromorphological study of building floors at Butser Experimental Farm, reported that trampling causes compaction of sediments that is observable in thin section. They also reported that trampling acts as a depositional process when clods of sediment are brought into a structure on the soles of people's feet. The compacted clods appear as lenses in thin section, and the repeated accumulation of these clods can form a laminated deposit, as described by Goldberg and Macphail (2006). Banerjea et al. (2013) note that these processes are more common when the substrate is damp. On the contrary, Nielsen (1991) reports that trampling can cause loosening of the surface, thereby increasing penetrability. Nielsen's results accord with experiments conducted by Rentzel and Narten (2000), who report the development of a granular microstructure in the upper millimeter of a deposit following trampling.

The results of these trampling experiments have been successfully applied in studies of archaeological deposits. For example, Goldberg et al. (2009) and Miller et al. (2013) describe the various effects that trampling had on the micromorphological character of the deposits in the Middle Stone Age rock-shelters of Diepkloof and Sibudu, South Africa. They noted that, in earlier phases of occupation, trampling led to horizontal reworking of sediment; at Diepkloof, they noted that this horizontal displacement was associated with the formation of a -millimeter-thin granular microstructure at the surface of the deposits, similar to what Rentzel and Narten (2000) reported in their experiments. In later phases of occupation at both sites, horizontal displacement was minimal, but in situ snapped and crushed bones were common. They suggest that this variation in the effects of trampling is related to changes in the type of substrate that was subjected to trampling: horizontal displacement and surficial, granular microstructure developed when people walked on a loose, dry surface. In situ crushing and snapping occurred when people walked on surfaces prepared with plant bedding.

The numerous experimental and archaeological studies of trampling show that it is an important process in the formation of archaeological sites, and its study can provide valuable information about stratigraphic integrity and human behavior. The numerous studies also show, however, that trampling can have diverse effects that vary significantly based on the nature of the artifacts and deposits.

Bibliography

Banerjea, R. Y., Bell, M., Matthews, W., and Brown, A., 2013. Applications of micromorphology to understanding activity areas and site formation processes in experimental hut floors. *Archaeological and Anthropological Sciences*, **7**(1), 89–112.

Bordes, F., and Bourgon, M., 1951. Le complexe Moustérien: Moustérien, Levalloisien et Tayacien. *L'Anthropologie*, **55**, 1–23.

Eren, M. I., Durant, A., Neudorf, C., Haslam, M., Shipton, C., Bora, J., Korisettar, R., and Petraglia, M., 2010. Experimental examination of animal trampling effects on artifact movement in dry and water saturated substrates: a test case from South India. *Journal of Archaeological Science*, **37**(12), 3010–3021.

Goldberg, P., and Macphail, R. I., 2006. *Practical and Theoretical Geoarchaeology*. Malden: Blackwell.

Goldberg, P., Miller, C. E., Schiegl, S., Ligouis, B., Berna, F., Conard, N. J., and Wadley, L., 2009. Bedding, hearths, and site maintenance in the Middle Stone Age of Sibudu Cave, KwaZulu-Natal, South Africa. *Archaeological and Anthropological Sciences*, **1**(2), 95–122.

McBrearty, S., Bishop, L., Plummer, T., Dewar, R., and Conard, N., 1998. Tools underfoot: human trampling as an agent of lithic artifact edge modification. *American Antiquity*, **63**(1), 108–129.

Miller, C. E., Conard, N. J., Goldberg, P., and Berna, F., 2010. Dumping, sweeping and trampling: Experimental micromorphological analysis of anthropogenically modified combustion features. In Théry-Parisot, I., Chabal, L., and Costamagno, S. (eds.), *The Taphonomy of Burned Organic Residues and Combustion Features in Archaeological Contexts*. Centre D'Études Préhistoire, Antiquité, Moyen Âge – UMR 6130, Proceedings of the Round Table, Valbonne, May 27–29, 2008. *P@lethnology*, **2010**(2), 25–37.

Miller, C. E., Goldberg, P., and Berna, F., 2013. Geoarchaeological investigations at Diepkloof Rock Shelter, Western Cape, South Africa. *Journal of Archaeological Science*, **40**(9), 3432–3452.

Nielsen, A. E., 1991. Trampling the archaeological record: an experimental study. *American Antiquity*, **56**(3), 483–503.

Rentzel, P., and Narten, G.-B., 2000. Zur Entstehung von Gehniveaus in sandig-lehmigen Ablagerungen. Experimente und archäologische Befunde. *Jahresbericht der Archäologischen Bodenforschung des Kantons Basel-Stadt*, **1999**, 107–127.

Villa, P., and Courtin, J., 1983. The interpretation of stratified sites: a view from underground. *Journal of Archaeological Science*, **10**(3), 267–281.

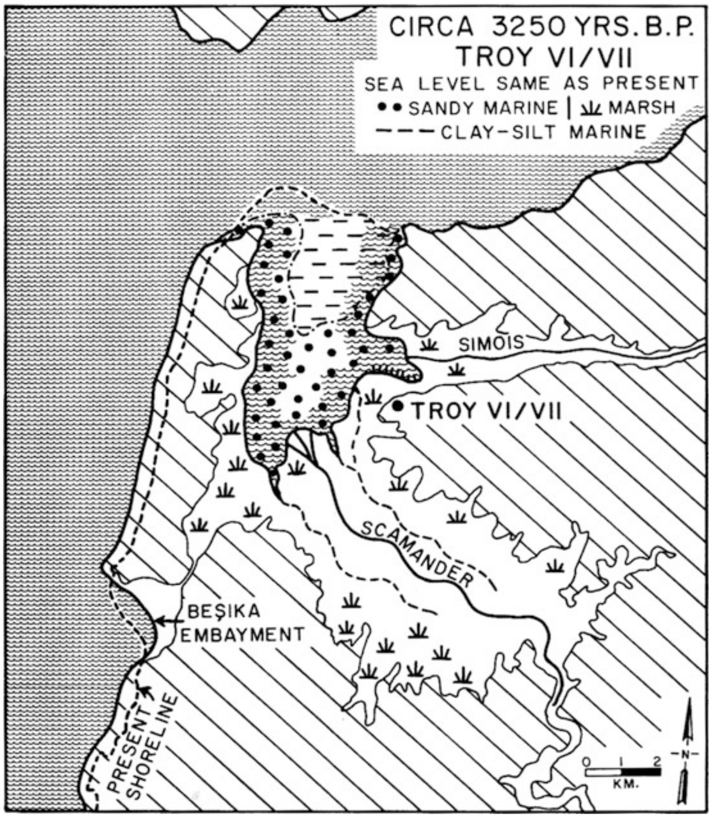
Cross-references

Soil Micromorphology

TROY

George Rip Rapp
Department of Geological Sciences, University of Minnesota, Duluth, MN, USA

Troy and the events on the Trojan plain described in Homer's *Iliad* have held a prominent place in history as a focus of human fascination for 3,000 years. Since the time of Strabo, 2,000 years ago, the geomorphic features



Troy, Figure 1 Paleogeographic reconstruction of the Scamander and Simoeis river valleys at the time of Troy VI and VII (thirteenth century BC) showing the marine embayment north of the city and the Beşika embayment to the west on the Aegean Coast where the Greek force might have landed (From Kraft et al. (1982, 36)).

of the Trojan plain (where the battles were fought) have been of scholarly interest. Strabo (1960:13.1.31) recognized that the Simoeis (Dümrek) and Scamander (Küçük Menderes) rivers merged on the plain near Troy, and "since they carry down a great quantity of silt they advance the coastline and create a blind mouth, and saltwater lagoons, and marshes" (Luce, 2003). Much modern debate has centered on the location and geomorphology of the coastline of the Trojan plain at the time of the Trojan War. In the 90 years from 1822 to 1912, Maclaren, Spratt, and Leaf published geographic information about the Trojan plain (Kraft et al., 2003). This also is the period when Schliemann excavated, on and off, at Troy between 1871 and 1890. Maclaren (1822) suggested that in Homeric times, the coast at the mouth of the Scamander and Simoeis rivers was well inland of its present position. Yet Maclaren drew a map of the "Ancient Coast and Greek Camp" with the Greek camp at the nineteenth century mouth of the Scamander, an unlikely situation given the long history of alluvial aggradation within the valley.

Beginning in 1977, an international team began an intensive coring program to detail the geomorphic changes in the Trojan coastline and on the Trojan plain. In a summary paper (Kraft et al., 2003), the authors concluded, "The reality of Homer's description of place, event, and topography correlated with geologic investigation helps show that the *Iliad* is consistent with paleogeographic reconstructions." An excellent summary of the history of work on the Trojan Plain is given by Luce (1998).

Coring determined that the Scamander and Simoeis valleys had become marine embayments with the rising of sea level after the Late Glacial Maximum; they were flooded to the ends of their respective coastal plains by 5000 BC. At the beginning of settlement at Troy (Troy I and II; early to mid third millennium BC), the Scamander Valley had filled with alluvium to a point several hundred meters north of the site, and a narrow coastal plain separated the site from the beach of a marine embayment of some 15 km in length that connected Troy to the Dardanelles Strait and the sea (Figure 1). This beach could have served as a harbor for an early Trojan fleet.

The exposed beachhead within the embayment has seemed to many a poor choice for the attacking Greek fleet at the moment of the Trojan War (Troy VIIa; thirteenth century BC), so a hypothesis has been proposed that the main Greek force landed within the Beşika embayment along the Aegean Coast (Figure 1). This location would have provided more cover yet still provided ready access to the Trojan plain, where combat took place according to the sources (Kraft et al., 1982, 37–40).

Troy was largely in ruins in Homer's day, but the remains of the Troy VI/VIIa citadel likely were still impressive. The ravages of time combined with sediment deposition drastically altered the site over subsequent millennia. In 1988, the Turkish government gave Manfred Korfmann an excavation permit for Troy itself (now known internationally as Troia). He assembled an international team to excavate and study the remains. The excavations have been quite successful considering that Schliemann, Blegen, and others had already done major digging there. A highly significant result of the Korfmann excavations has been the verification of the existence of a lower settlement from the seventeenth to the early twelfth centuries BCE (levels VI/VIIa) outside and south and east of the citadel. Magnetometer surveys and seven excavations since 1993 have shown that this lower city was surrounded at least in the thirteenth century by an impressive U-shaped fortification ditch. The layout of the lower settlement was confirmed by an intensive and systematic pottery survey in 2003. The results have demonstrated that Troy, which now covers about 75 acres, is about 15 times larger than was previously thought.

The results of these excavations and related studies have been published in a yearly series of volumes with the title *Studia Troica*. Volume I was published in 1991; volume 18 appeared in 2009. It should be noted that in addition to the prehistoric levels, extensive Roman remains have been excavated and studied.

Bibliography

Kraft, J. C., Kayan, İ., and Erol, O., 1982. Geology and paleogeographic reconstructions of the vicinity of Troy. In Rapp, G. R., Jr., and Gifford, J. A. (eds.), *Troy: The Archaeological Geology*. Princeton: Princeton University Press. Supplementary Monograph, 4, pp. 11–41.

Kraft, J. C., Rapp, G. R., Kayan, İ., and Luce, J. V., 2003. Harbor areas at ancient Troy: sedimentology and geomorphology complement Homer's Iliad. *Geology*, **31**(2), 163–166.

Luce, J. V., 1998. *Celebrating Homer's Landscapes: Troy and Ithaca Revisited*. New Haven: Yale University Press.

Maclaren, C., 1822. *A Dissertation on the Topography of the Plain of Troy*. Edinburgh: printed for A. Constable.

Strabo. 1960. *The Geography of Strabo*. Transl. by Jones, H. L. Loeb Classical Library. Cambridge, MA: Harvard University Press.

Cross-references

Coastal Settings
Harbors and Ports, Ancient

TSUNAMIS

Beverly N. Goodman-Tchernov
Moshe Strauss Department of Marine Geosciences, Leon Charney School of Marine Sciences, University of Haifa, Haifa, Israel

Synonyms

Seismic sea wave; Tidal wave (erroneous)

Definition

Tsunami: Japanese "harbor wave."

Tsunami: long-length waves in a body of water (usually large lake or sea), generated by the substantial displacement of water.

Introduction

Human populations have long shown a preference for settling in coastal zones. The coastline is a meeting point between different resource zones and a doorway to efficient and economical water-based transport for trade. However, this rich and attractive location can also be vulnerable to forces of nature with gradual or rapid disastrous consequences such as sea-level change, hurricanes, and tsunamis. Tsunamis occur in a relatively short period of time. The warnings, if recognized, are rarely more than a half day in advance and more likely a matter of minutes to hours. The size of a tsunami varies greatly, ranging from waves that only slightly alter a typical day's tide gauge record to mega-tsunamis with the potential of wave heights in the tens of meters and inundation values over 1 km. In recent years, multiple mega-tsunamis (e.g., December 26, 2004, and July 17, 2006, in the Indian Ocean and March 11, 2011, in Tohoku, Japan; see recent discussion in Goff et al., 2012) have heightened the attention and awareness of this phenomenon and directed greater interest into the impact tsunamis have had on coastlines in the past. Archaeological coastal sites have provided some insight into understanding the impact of tsunamis over time, and geoarchaeological studies of coastal sites are at the forefront of this field.

Tsunami dynamics

Tsunamis are propagated by a sudden displacement of water that results in a wave characterized by a substantially long wavelength and greater potential for inshore run-up relative to meteorologically driven waves. The causes of tsunamis include earthquakes (subaerial and terrestrial), landslides, subaerial slumping, volcanic eruptions, meteorites, glacial felling, and explosions. While, at sea, a tsunami's wave height might be considered negligible, its wavelength can be as long as hundreds of kilometers. In contrast, large storm waves have a wavelength of 30–40 m. As the tsunami wave approaches a coastline, the shallower water depth slows the overall speed of the wave and compresses its full volume, resulting in increasing wave heights. This volume of water can then flow far inland until the wave's energy dissipates. Damages to coastal settlements resulting from tsunami impact range from insignificant to completely devastating, depending on the specific dynamics of the wave, the preparedness of the human population (particularly whether evacuation has occurred), the extent of coastal development, and the specific character of the coastline. The most vulnerable sites are those located along the coastlines, especially within harbors or estuaries where the tsunami flow is known to travel even further inland, become magnified due to reflective waves, and sometimes gain wave height.

Historical evidence of tsunami events

Written descriptions of events are important resources for reconstructing tsunami events of the past. Sources range from religious tracts, governmental records, requests for assistance, insurance maps, and historical accounts. These descriptions have been compiled into more comprehensive catalogues, traditionally presented in tandem with earthquake records, but sometimes presented independently (e.g., Lockridge and Dunbar, 1996). In areas more extensively studied, separate catalogues exist for discrete regions (e.g., Australia, Italy, Cyprus, Greece, the Eastern Mediterranean, Turkey, the Pacific Ocean, Central America, the Middle East; Soloviev et al., 1986; Molina, 1997; Fernandez et al., 2000; Riad et al., 2003; Tinti et al., 2004; Dominey-Howes, 2007; Fokaefs and Papadopoulos, 2007; Papadopoulos et al., 2007; Ambraseys and Synolakis, 2010; Altinok et al., 2011; Papadopoulos et al., 2014). These catalogues present a summary of information and known sources that provide information about past tsunamis. Some catalogues contain the source information translated into a single language, together with the original source reference, but unfortunately, the original source is sometimes difficult to access, and only translations are available. This, and other variables, can lead to complications when assessing the reliability of the information.

Common methods for determining the reliability of a written text include determining whether (1) the source is first, second, or third hand; (2) it is contemporaneous with the event or a later recollection; (3) a number of sources corroborate the same event; and (4) related accounts of simultaneous trigger events exist (e.g., earthquakes or volcanic eruptions; see Salamon et al., 2007) and (5) more recently the publication or report of field evidence. Reliability is a problem, as written records sometimes provide erroneous information for a multitude of reasons, including issues with varying calendar systems, tendencies toward exaggeration, poor information transfer, bad translation, the merging of near-contemporaneous events, or the separation of single events into multiple occurrences (Karcz, 2004). Despite these issues, the historical record remains a critical source for reconstructing historical tsunami events.

Instrumentally recorded events are available for the twentieth century to the present. These records come from tidal and wave records, aerial photographs, and more recently satellite imagery, deep-sea wave recorders, and tsunami and earthquake warning systems. Over time, more instruments are being added around the world, and in the future there should be fewer events that occur without being recorded and measured instrumentally.

Paleotsunami research

Reconstructing the occurrence of tsunamis in the past offers a means to estimate the risk for future tsunamis. Tsunamis that date prior to the historical record, or for which there are no written observations, are called "paleotsunamis" (International Tsunami Information Center, 2011). The majority of field research directed at identifying paleotsunamites (sedimentological markers of paleotsunami events) has focused on evidence for marine incursion into terrestrial areas (see discussion in Scheffers and Kelletat, 2003; Dawson and Stewart, 2007). These deposits are especially reliable, as they demonstrate specific movement of marine water above and beyond the usual storm wave zone of influence, an important criterion for properly labeling the event a tsunami rather than storm related (Goff et al., 2004; Morton et al., 2007; Ramírez-Herrera et al., 2012). Stratigraphic sequences in the terrestrial realm, such as those identified during coring or trenching campaigns, might reveal signs of previous tsunami events. Among the proxies that have been used for recognizing these changes include (1) the presence of marine-specific fauna in a setting that is otherwise terrestrial, brackish, or freshwater, (2) changes in sediment grain size, (3) marine-associated organisms within the sands or sediments, (4) erosional bottom contacts, and (5) unusual inclusions of foreign origin (Goff et al., 2012). While, in some cases, affected sites are abandoned after a tsunami strike, some sites are also regularly rebuilt and renewed following the destructive events, and this makes recognizing tsunami deposits or damage within an archaeological site complicated. Therefore, nearby sediment traps in less-inhabited areas (lake bottoms, lagoons, and artificial reservoirs) sometimes preserve more evidence of the event, which can be extrapolated to destruction sequences within archaeological sites based on age.

Evidence of tsunamis at archaeological sites

Coastal archaeological sites are particularly vulnerable to tsunami-related damages. Written records of a tsunami event might be produced when there is an occupied site that is impacted by the event. If a coastline lacks any settlements (or settlements of consequence to those recording the history), it is less likely that the event will be documented in the written record. Simultaneously, the preservation of tsunami deposits is problematic, particularly at occupied sites where rebuilding and post-tsunami cleanup further alters or erases the deposits that may be ephemeral to start.

Evidence for paleotsunami events using field techniques with geoarchaeological components has been published at a few archaeological sites worldwide including Egypt (Guidoboni et al., 1994; Stanley and Bernasconi, 2006; Hamouda, 2009), Lebanon (Morhange et al., 2006), Israel (Reinhardt et al., 2006; Goodman-Tchernov et al., 2009), Crete (Scheffers and Scheffers, 2007; Bruins et al., 2008), the UK (Dawson et al., 1988, 1990), Greece (Vött et al., 2010), and New Zealand (Goff and McFadgen, 2003; Goff et al., 2010). In some cases, studies have been conducted by reviewing and reinterpreting the causes of destruction or abandonment phases published in earlier excavation reports, such as the case of Atlit Yam (Pareschi et al., 2007; as refuted by Galili et al., 2008) and Knossos, Crete (Antonopoulos, 1992; as refuted by Minoura et al., 2000), and New Zealand prehistoric Maori sites (the reassessment by Goff and McFadgen, 2003, of the conclusions of Leach and Leach, 1979). In these cases, a reconsideration of the original findings – and in the Maori case including consideration of nearby physical findings in the non-anthropogenically altered environment – led the researchers to assign a tsunami-related cause to the damage seen at the sites. Tectonic activity and/or tsunami inundation was suggested as the major factor behind the abandonment and movement of North American west coast sites in British Columbia, Canada (Hutchinson and McMillan, 1997), as well as coastal sites in Washington State and Oregon (Woodward et al., 1990; Cole et al., 1996).

A multitude of indicators have been used to suggest tsunami-related damage at archaeological sites. With regard to physical evidence, the most important aspect appears to be the context of the deposit rather than any single feature of the deposits themselves. It is important to note that tsunami deposits can reflect only the materials and sediments supplied at that particular site, so many features may be site specific. For example, if the inhabitants of a site were regularly discarding marine shell into a freshwater lake, then marine shell in the freshwater lake itself cannot be indicative of a past tsunami. However, a sudden change in quantity, species, or individual character of those shells (breakage/wear) would have significance as would the sudden appearance of a shell horizon at a site where such activities were absent. Among the features that have been used to represent tsunamis at archaeological sites (see Goff et al., 2012, for a full summary) are (1) tilted, damaged, or altered marine installations such as harbor features or coastal constructions, (2) unusual changes in grain size distribution within sediments, (3) hiatuses or eroded horizons, (4) burials that appear disturbed or do not fit recognized cultural norms, (5) marine micro- and/or macro-paleontological deposits (e.g., pollen, thecamoebians, foraminifera, ostracods, mollusks, gastropods) distributed out of context or with unusual taphonomic features, (6) abandonment sequences contemporaneous with such features, and (7) unbroken or freshly broken and deposited ceramics or other cultural material offshore without explanatory context (shipwreck, construction fill, garbage pits). All investigations benefit from a wide geographical study of stratigraphic sequences to be able to demonstrate the presence of these unusual horizons, particularly given the common changes in their appearance depending on the dynamics of the particular geography and the variations in local source materials. In Caesarea, Israel, for example, over three tsunamis were identified in offshore cores and in excavations, and each one varied somewhat with regard to tsunami-related indicators. Many of these variations could be attributed to differences in the landscape at the time of the event, especially for events that occurred prior to heavy human occupation and therefore lacked many indicators of anthropogenic origin (ceramics, damaged harbor features, etc.; Goodman et al., 2009).

Summary

The study of tsunamis at archaeological sites is a young field. In time, as the study of field deposits from modern tsunami events advances and knowledge of their expression and dynamics grows, we can expect more descriptions of tsunami-derived deposits at archaeological sites as well. The possibility of tsunami events should always be considered when studying archaeological sites located on coastlines, particularly those in seismically active zones.

Bibliography

Altinok, Y., Alpar, B., Özer, N., and Aykurt, H., 2011. Revision of the tsunami catalogue affecting Turkish coasts and surrounding regions. *Natural Hazards and Earth System Sciences*, **11**(2), 273–291.

Ambraseys, N., and Synolakis, C., 2010. Tsunami catalogs for the Eastern Mediterranean, revisited. *Journal of Earthquake Engineering*, **14**(3), 309–330.

Antonopoulos, J., 1992. The great Minoan eruption of Thera volcano and the ensuing tsunami in the Greek archipelago. *Natural Hazards*, **5**(2), 153–168.

Bruins, H. J., MacGillivray, J. A., Synolakis, C. E., Benjamini, C., Keller, J., Kisch, H. J., Klügel, A., and van der Plicht, J., 2008. Geoarchaeological tsunami deposits at Palaikastro (Crete) and the Late Minoan IA eruption of Santorini. *Journal of Archaeological Science*, **35**(1), 191–212.

Cole, S. C., Atwater, B. F., McCutcheon, P. T., Stein, J. K., and Hemphill- Haley, E., 1996. Earthquake-induced burial of archaeological sites along the southern Washington coast about A. D. 1700. *Geoarchaeology*, **11**(2), 165–177.

Dawson, A. G., and Stewart, I., 2007. Tsunami deposits in the geological record. *Sedimentary Geology*, **200**(3–4), 166–183.

Dawson, A. G., Long, D., and Smith, D. E., 1988. The storegga slides: evidence from Eastern Scotland for a possible tsunami. *Marine Geology*, **82**(3–4), 271–276.
Dawson, A. G., Smith, D. E., and Long, D., 1990. Evidence for a tsunami from a Mesolithic site in Inverness, Scotland. *Journal of Archaeological Science*, **17**(5), 509–512.
Dominey-Howes, D., 2007. Geological and historical records of tsunami in Australia. *Marine Geology*, **239**(1–2), 99–123.
Fernandez, M., Molina, E., Havskov, J., and Atakan, K., 2000. Tsunamis and tsunami hazards in Central America. *Natural Hazards*, **22**(2), 91–116.
Fokaefs, A., and Papadopoulos, G. A., 2007. Tsunami hazard in the Eastern Mediterranean: strong earthquakes and tsunamis in Cyprus and the Levantine Sea. *Natural Hazards*, **40**(3), 503–526.
Galili, E., Horwitz, L. K., Hershkovitz, I., Eshed, V., Salamon, A., Zviely, D., Weinstein-Evron, M., and Greenfield, H., 2008. Comment on "Holocene tsunamis from Mount Etna and the fate of Israeli Neolithic communities" by Maria Teresa Pareschi, Enzo Boschi, and Massimiliano Favalli. *Geophysical Research Letters*, **35**(8), L08311, doi:10.1029/2008GL033445.
Goff, J. R., and McFadgen, B. G., 2003. Large earthquakes and the abandonment of prehistoric coastal settlements in 15th century New Zealand. *Geoarchaeology*, **18**(6), 609–623.
Goff, J., McFadgen, B. G., and Chagué-Goff, C., 2004. Sedimentary differences between the 2002 Easter storm and the 15th-century Okoropunga tsunami, southeastern North Island, New Zealand. *Marine Geology*, **204**(1–2), 235–250.
Goff, J., Pearce, S., Nichol, S. L., Chagué-Goff, C., Horrocks, M., and Strotz, L., 2010. Multi-proxy records of regionally-sourced tsunamis, New Zealand. *Geomorphology*, **118**(3–4), 369–382.
Goff, J., Chagué-Goff, C., Nichol, S., Jaffe, B., and Dominey-Howes, D., 2012. Progress in palaeotsunami research. *Sedimentary Geology*, **243–244**, 70–88.
Goodman-Tchernov, B. N., Dey, H. W., Reinhardt, E. G., McCoy, F., and Mart, Y., 2009. Tsunami waves generated by the Santorini eruption reached Eastern Mediterranean shores. *Geology*, **37**(10), 943–946.
Guidoboni, E., Comastri, A., and Traina, G., 1994. *Catalogue of Ancient Earthquakes in the Mediterranean Area up to the 10th Century*. Rome: Istituto Nazionale di Geofisica.
Hamouda, A. Z., 2009. A reanalysis of the AD 365 tsunami impact along the Egyptian Mediterranean coast. *Acta Geophysica*, **58**(4), 687–704.
Hutchinson, I., and McMillan, A. D., 1997. Archaeological evidence for village abandonment associated with late Holocene earthquakes at the Northern Cascadia subduction zone. *Quaternary Research*, **48**(1), 79–87.
International Tsunami Information Center, 2011. http://itic.ioc-unesco.org/index.php
Karcz, I., 2004. Implications of some early Jewish sources for estimates of earthquake hazard in the Holy Land. *Annals of Geophysics*, **47**(2–3), 759–792.
Leach, F., and Leach, H. M. K. (eds.), 1979. *Prehistoric Man in Palliser Bay*. Wellington: National Museum of New Zealand. Bulletin 21.
Lockridge, P. A., and Dunbar, P. K., 1996. *Worldwide Tsunamis: 2000 B.C.–1995*. Boulder: NOAA/NGDC Publication and Database.
Minoura, K., Imamura, F., Kuran, U., Nakamura, T., Papadopoulos, G. A., Takahashi, T., and Yalciner, A. C., 2000. Discovery of Minoan tsunami deposits. *Geology*, **28**(1), 59–62.
Molina, E., 1997. *Tsunami Catalogue for Central America, 1539–1996*. Bergen: Institute of Solid Earth Physics, University of Bergen, Norway. Report No. II 1–04.
Morhange, C., Marriner, N., and Pirazzoli, P. A., 2006. Evidence of late-Holocene tsunami events in Lebanon. *Zeitschrift für Geomorphologie NF*, **146**(Suppl.), 81–95.
Morton, R. A., Gelfenbaum, G., and Jaffe, B. E., 2007. Physical criteria for distinguishing sandy tsunami and storm deposits using modern examples. *Sedimentary Geology*, **200**(3–4), 184–207.
Papadopoulos, G. A., Daskalaki, E., Fokaefs, A., and Giraleas, N., 2007. Tsunami hazards in the Eastern Mediterranean: strong earthquakes and tsunamis in the east Hellenic arc and trench system. *Natural Hazards and Earth System Sciences*, **7**(1), 57–64.
Papadopoulos, G. A., Gràcia, E., Urgeles, R., Sallares, V., De Martini, P. M., Pantosti, D., González, M., Yalciner, A. C., Mascle, J., Sakellariou, D., Salamon, A., Tinti, S., Karastathis, V., Fokaefs, A., Camerlenghi, A., Novikova, T., and Papageorgiou, A., 2014. Historical and pre-historical tsunamis in the Mediterranean and its connected seas: geological signatures, generation mechanisms and coastal impacts. *Marine Geology*, **354**, 81–109.
Pareschi, M. T., Boschi, E., and Favalli, M., 2007. Holocene tsunamis from Mount Etna and the fate of Israeli Neolithic communities. *Geophysical Research Letters*, **34**(16), L16317, doi:10.1029/2007GL030717.
Ramírez-Herrera, M.-T., Lagos, M., Hutchinson, I., Kostoglodov, V., Machain, M. L., Caballero, M., Goguitchaichvili, A., Aguilar, B., Chagué-Goff, C., Goff, J., Ruiz-Fernández, A.-C., Ortiz, M., Nava, H., Bautista, F., Lopez, G. I., and Quintana, P., 2012. Extreme wave deposits on the pacific coast of Mexico: tsunamis or storms? – A multi-proxy approach. *Geomorphology*, **139–140**, 360–371.
Reinhardt, E. G., Goodman, B. N., Boyce, J. I., Lopez, G., van Hengstum, P., Rink, W. J., Mart, Y., and Raban, A., 2006. The tsunami of 13 December A.D. 115 and the destruction of Herod the Great's harbor at Caesarea Maritima, Israel. *Geology*, **34**(12), 1061–1064.
Riad, S., El-Hadidy, S., Mohamed, A. E. A., Tealeb, A. A., Basta, N. Z., Aziz, M. A. A., and Khalil, H. A., 2003. *Ancient Earthquakes from some Arabic Sources and Catalogue of Middle East Historical Earthquakes*. National Research Institute of Astronomy and Geophysics (Egypt). UNDP/UNESCO Geo-development Project for Capacity Building of the Egyptian Geological Survey and Mining Authority.
Salamon, A., Rockwell, T., Ward, S. N., Guidoboni, E., and Comastri, A., 2007. Tsunami hazard evaluation of the Eastern Mediterranean: historical analysis and selected modeling. *Bulletin of the Seismological Society of America*, **97**(3), 705–724.
Scheffers, A., and Kelletat, D., 2003. Sedimentologic and geomorphologic tsunami imprints worldwide – a review. *Earth-Science Reviews*, **63**(1–2), 83–92.
Scheffers, A., and Scheffers, S., 2007. Tsunami deposits on the coastline of west Crete (Greece). *Earth and Planetary Science Letters*, **259**(3–4), 613–624.
Soloviev, S. L., Go, C. N., and Kim, K. C., 1986. *Katalog tsunami v Tikhom okeane, 1969–1982 gg [Catalog of Tsunamis in the Pacific Ocean, 1969–1982]*. Moscow: Akademiia nauk SSSR, Izdatel'stvo Mezhduvedomstvennyi geofizicheskii kom-t. In Russian.
Stanley, J.-D., and Bernasconi, M. P., 2006. Holocene depositional patterns and evolution in Alexandria's Eastern Harbor, Egypt. *Journal of Coastal Research*, **22**(2), 283–297.

Tinti, S., Maramai, A., and Graziani, L., 2004. The new catalogue of Italian tsunamis. *Natural Hazards*, **33**(3), 439–465.

Vött, A., Lang, F., Brückner, H., Gaki-Papanastassiou, K., Maroukian, H., Papanastassiou, D., Giannikos, A., Hadler, H., Handl, M., Ntageretzis, K., Willershäuser, T., and Zander, A., 2010. Sedimentological and geoarchaeological evidence of multiple tsunamigenic imprint on the bay of Palairos-Pogonia (Akarnania, NW Greece). *Quaternary International*, **242**(1), 213–239.

Woodward, J., White, J., and Cummings, R., 1990. Paleoseismicity and the archaeological record: areas of investigation on the northern Oregon coast. *Oregon Geology*, **52**(3), 57–65.

Cross-references

Coastal Settings
Grain Size Analysis
Harbors and Ports, Ancient
Paleoenvironmental Reconstruction
Paleoshores (Lakes and Sea)
Santorini
Sedimentology
Submerged Continental Shelf Prehistory

U

'UBEIDIYA

Carolina Mallol
Departamento de Geografía e Historia, Universidad de La Laguna, Tenerife, Spain

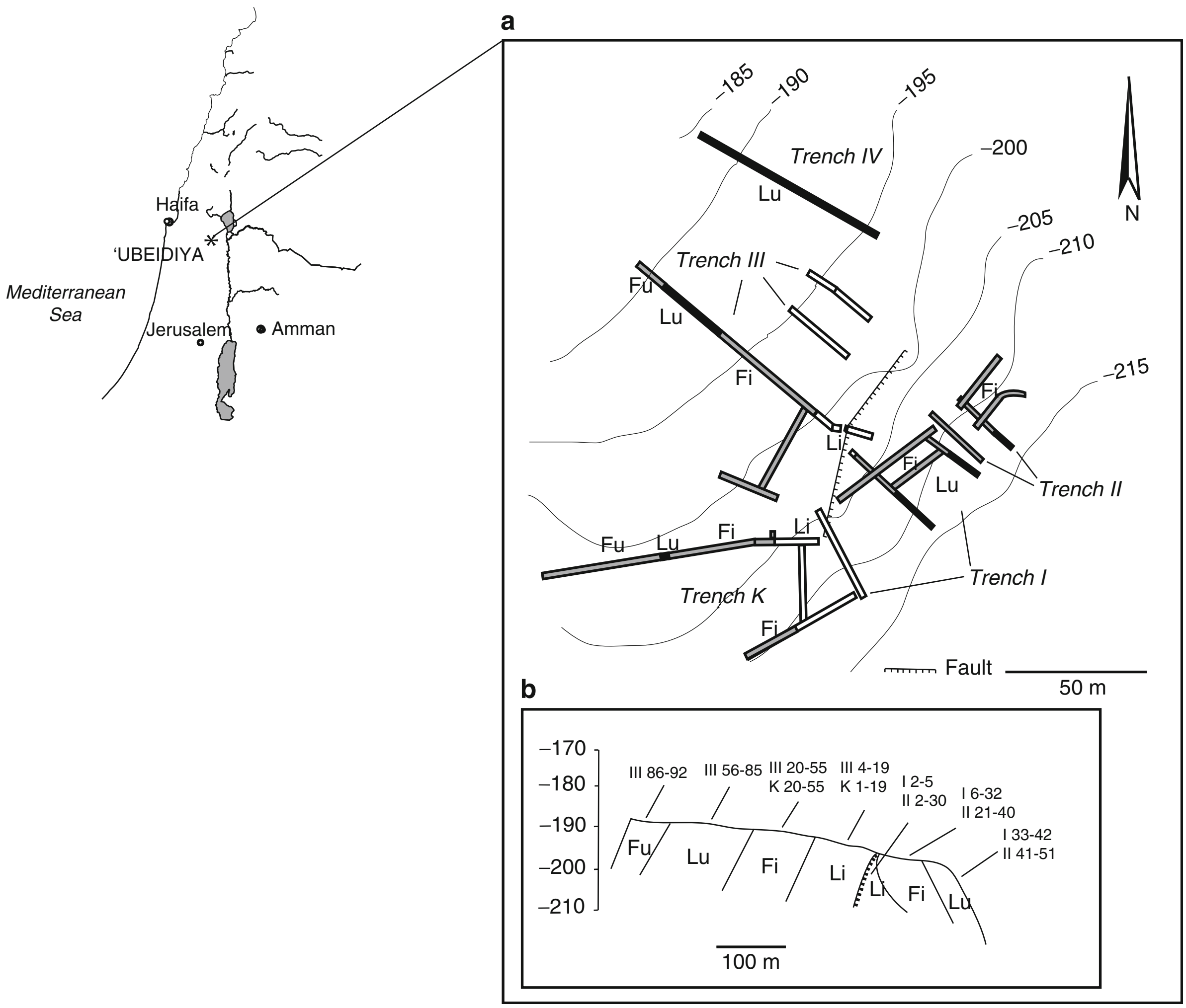
Definition

'Ubeidiya is a Lower Pleistocene archaeological site located in the Jordan Valley, 3 km south of the shores of the present-day Sea of Galilee (Figure 1). The site represents a fluviolacustrine stratified sequence of tilted graben sediments known as the 'Ubeidiya Formation (Picard and Baida, 1966). This formation, which has been dated by paleomagnetism and biochronology to ca. 1.6–1.2 Ma (Tchernov, 1986, 1987; Braun et al., 1991; Verosub and Tchernov, 1991; Heimann and Braun, 2000; Belmaker et al., 2002; Feibel, 2004; Sagi et al., 2005), is faulted and folded as part of an anticline that strikes to the NNE, forming minor anticlines and synclines at the site. As a result, the 'Ubeidiya stratigraphic layers are tilted, some of them up to 90°. The 'Ubeidiya Formation comprises four members representing an alternation of fluvial (F) and limnic (L) facies with a total thickness of about 154 m; in stratigraphic order from lower to upper, they are Li (52 m), Fi (20–30 m), Lu (56 m), and Fu (16 m) (Bar-Yosef and Goren-Inbar, 1993) (see Figure 1a, b).

The site was excavated in phases, first by M. Stekelis in 1960–1966 and later by O. Bar-Yosef and E. Tchernov in 1967–1974. Additional excavations were carried out between 1988 and 1999 by O. Bar-Yosef, E. Tchernov, and J. Shea. The archaeological record reveals abundant Villafranchian and Galerian faunal remains as well as associated Acheulean stone tools representing abandoned early hominin living floors on the marshy and pebbly shores of a lake that were occupied throughout a regressive cycle (Fi) (Bar-Yosef and Tchernov, 1972; Bar-Yosef, 1989, 1994; Bar-Yosef and Goren-Inbar, 1993; Shea, 1999; Shea and Bar-Yosef, 1999; Belmaker et al., 2002; Belmaker, 2006).

Depositionally, the 'Ubeidiya Formation originated as a succession of alternating lacustrine (mudflats and shallow subaqueous muds), palustrine (distal mudflows), and fluvial (deltaic channel and floodplain) deposits, with a prevalence of the last. The Fi cycle deposits (Figure 2) have been distinguished by their micromorphological

A.S. Gilbert (ed.), *Encyclopedia of Geoarchaeology*, DOI 10.1007/978-1-4020-4409-0,



'Ubeidiya, Figure 1 Plan (**a**) and section (**b**) views of the excavation at 'Ubeidiya indicating the position and tilt of the different members of the 'Ubeidiya Formation (Li – *white*, Fi – *gray*, Lu – *black*, and Fu – *gray*). The position of some of the key lithostratigraphic units is indicated in (**b**). Roman numerals stand for their corresponding trench (Modified from Bar-Yosef and Goren-Inbar, 1993). The site is located below sea level, so the ground surface slopes downward to the southeast with increasing negative elevation.

features, which taken as a whole and in stratigraphic order suggest a recurrent sedimentation pattern involving deposition of fluvial sediment at the shoreline followed by prolonged periods of exposure under wet conditions (Mallol, 2006). Carnivore refuse and by-products of hominin activity accumulated periodically on the surfaces of each deposit.

Prolonged postdepositional surface exposure during the dry seasons resulted in the formation of archaeological palimpsests through repeated, overlapping hominin occupations, while fluvial discharge during the wet seasons triggered localized artifact and bone translocation and abrasion (Mallol, 2006).

The entire Fi regressive cycle entailed unvarying climatic conditions with seasonal fluctuations and episodic lacustrine incursions. A trend toward arid conditions emerges at the end, as evidenced by an increase in microscopic sedimentary desiccation features toward the top of the sequence (Mallol, 2006).

Human impact on the sediment was minimal at 'Ubeidiya. No signs of trampling or inclusion of microscopic anthropogenic debris have been found in the sediment that makes up the naturally deposited cobble floors (Figure 3), as well as the gravelly and muddy layers associated with the archaeological remains. No signs of anthropogenic fire have been identified.

'Ubeidiya, Figure 2 Field view of west face of Trench III showing some of the Fi cycle tilted units. Note the presence of high energy fluvial facies toward the top (*left* of the image) compared to previous floodplain facies underlying it to the *right* (Photo by Paul Goldberg).

'Ubeidiya, Figure 3 Field view of Trench I showing Fi layers I-26a (*right*; ladder leaning against it), I-26b (fine grained underlying *a*), and I-26c (cobble surface underlying *b* on the *left*) (Photo by Paul Goldberg).

Bibliography

Bar-Yosef, O., 1989. The excavations at 'Ubeidiya in retrospect: an eclectic view. In Bar-Yosef, O., and Vandermeersch, B. (eds.), *Investigations in South Levantine Prehistory*. Oxford: British Archaeological Reports. British Archaeological Reports, International Series, Vol. 497, pp. 101–111.

Bar-Yosef, O., 1994. The Lower Paleolithic of the Near East. *Journal of World Prehistory*, **8**(3), 211–265.

Bar-Yosef, O., and Goren-Inbar, N., 1993. *The Lithic Assemblages of 'Ubeidiya: A Lower Palaeolithic Site in the Jordan Valley*. Jerusalem: The Institute of Archaeology, Hebrew University of Jerusalem.

Bar-Yosef, O., and Tchernov, E., 1972. *On the Palaeo-Ecological History of the Site of 'Ubeidiya*. Jerusalem: Israel Academy of Sciences and Humanities.

Belmaker, M., 2006. *Community Structure Through Time: 'Ubeidiya, a Lower Pleistocene Site as a Case Study*. PhD dissertation. Jerusalem, The Hebrew University of Jerusalem.

Belmaker, M., Tchernov, E., Condemi, S., and Bar-Yosef, O., 2002. New evidence for hominid presence in the Lower Pleistocene of the Southern Levant. *Journal of Human Evolution*, **43**(1), 43–56.

Braun, D., Ron, H., and Marco, S., 1991. Magnetostratigraphy of the hominid tool-bearing Erk el Ahmar formation in the northern Dead Sea Rift. *Israel Journal of Earth Sciences*, **40**, 191–197.

Feibel, C. S., 2004. Quaternary lake margins of the Levant rift valley. In Goren-Inbar, N., and Speth, J. D. (eds.), *Human Paleoecology in the Levantine Corridor*. Oxford: Oxbow Books, pp. 21–36.

Heimann, A., and Braun, D., 2000. Quaternary stratigraphy of the Kinnarot Basin, Dead Sea Transform, northeastern Israel. *Israel Journal of Earth Sciences*, **49**(1), 31–44.

Mallol, C., 2006. What's in a beach? Soil micromorphology of sediments from the Lower Paleolithic site of 'Ubeidiya, Israel. *Journal of Human Evolution*, **51**(2), 185–206.

Picard, L., and Baida, U., 1966. *Geological Report on the Lower Pleistocene Deposits of the 'Ubeidiya Excavations*. Jerusalem: Israel Academy of Sciences and Humanities.

Sagi, A., Belmaker, M., Ron, H., Enzel, Y., Agnon, A., and Bar-Yosef, O., 2005. Paleomagnetic dating of 'Ubeidiya Formation. In Abramovich, S. (ed.), *Abstracts of the Israel Geological Society Annual Meeting (April 5–7, 2005)*. Jerusalem: Israel Geological Society, p. 101.

Shea, J. J., 1999. Artifact abrasion, fluvial processes, and "living floors" from Early Paleolithic site of 'Ubeidiya (Jordan Valley, Israel). *Geoarchaeology*, **14**(2), 191–207.

Shea, J. J., and Bar-Yosef, O., 1999. Lithic assemblages from new (1988–1994) excavations at 'Ubeidiya: a preliminary report. *Journal of the Israel Prehistoric Society*, **28**, 5–20.

Tchernov, E., 1986. *The Lower Pleistocene Mammals of 'Ubeidiya (Jordan Valley)*. Paris: Association Paléorient. Memoirs et Travaux du Centre de Recherche Français de Jerusalem, Vol. 5.

Tchernov, E., 1987. The age of 'Ubeidiya Formation, an early Pleistocene hominid site in the Jordan Valley, Israel. *Israel Journal of Earth Sciences*, **36**, 3–30.

Verosub, K., and Tchernov, E., 1991. Résultats préliminaires de l'étude magnétostratigraphique d'une séquence sédimentaire à l'industrie humaine en Israël. In Bonifay, E., and Vandermeersch, B. (eds.), *Les premiers Européens*. Paris: Éditions du C. T. H. S, pp. 237–242.

Cross-references

Lithics
Microstratigraphy
Paleoenvironmental Reconstruction
Paludal Settings (Wetland Archaeology)
Site Formation Processes
Soil Micromorphology

U-SERIES DATING

Robyn Pickering
School of Earth Sciences, University of Melbourne, Parkville, Victoria, Australia

Synonyms

Thorium-230 (^{230}Th) dating; Uranium disequilibrium (^{234}U/^{238}U) dating; Uranium-lead (U-Pb) dating; Uranium-series disequilibrium dating; Uranium-thorium (U-Th) dating

Definition

Uranium-series dating is a broad term covering a number of geological dating schemes based on the measurement of the natural radioactivity of uranium isotopes U-238 (^{238}U) and U-235 (^{235}U), as well as their daughter isotopes in material which initially contained only the parent uranium.

Uranium-lead (*U-Pb*) *dating* uses the amount of stable ^{206}Pb, the end product of the ^{238}U decay chain, relative to the amount of initial ^{238}U to calculate the time of formation (and thus age) of a sample.

Uranium-thorium (*U-Th*) *dating* is a specific method that uses only a section of the ^{238}U decay chain to calculate the time of formation (and thus age) based on the degree to which equilibrium has been restored between the radioactive daughter isotope thorium-230 (^{230}Th) and its radioactive parent, ^{238}U.

Introduction

U-series dating has had a profound impact on the earth sciences in providing ages for the Earth itself and Quaternary science in particular. It is one of the most widely used dating techniques after radiocarbon. The history of its development begins with the seminal work of Marie Curie in the early 1900s that led to the discovery of the ^{238}U decay chain and natural radioactivity. The years following World War II saw the development of the U-series technique, which was primarily applied to dating deep-ocean sediments. During the 1960s, the method was expanded to include dating of both marine and terrestrial carbonates, which remain the central focus today. As with radiocarbon, U-series dating has benefitted greatly from the application of mass spectrometry, with significant advances taking place during the 1980s, as well as within the last 10 years, yielding improvements in both precision and accuracy.

Uranium (U) is present as a trace element in all natural materials, and it occurs as six isotopes ranging in atomic weight from U-233 to U-238. ^{238}U is by far the most common isotope, making up 99.27 % of all known uranium, with ^{235}U the next most abundant at only 0.72 %. All the other isotopes occur at very minimal levels (Grenthe et al., 2011). The U-series dating technique is based on the natural decay of ^{238}U to lead-206 (^{206}Pb), with a half-life of 4.47 billion years, and of ^{235}U to lead-207 (^{207}Pb), with a half-life of 704 million years (Grenthe et al., 2011) (Figure 1).

The systematics of U-series dating are complicated, and a specialist will generally undertake the analysis. This entry is an overview of the essential concepts behind the method, a summary of the laboratory techniques and advances, and a review of some applications to archaeology. Other very good general overviews are provided by Schwarcz (1989, 1992), Smart (1991), Latham (2001), Pike and Pettitt (2003), and Walker (2005). More detailed, technical reviews of the method and its applications can be found in the edited volumes by Ivanovich and Harmon (1992) and Bourdon et al. (2003). The rapidly advancing field of U-Pb dating of carbonates is reviewed in Rasbury and Cole (2009).

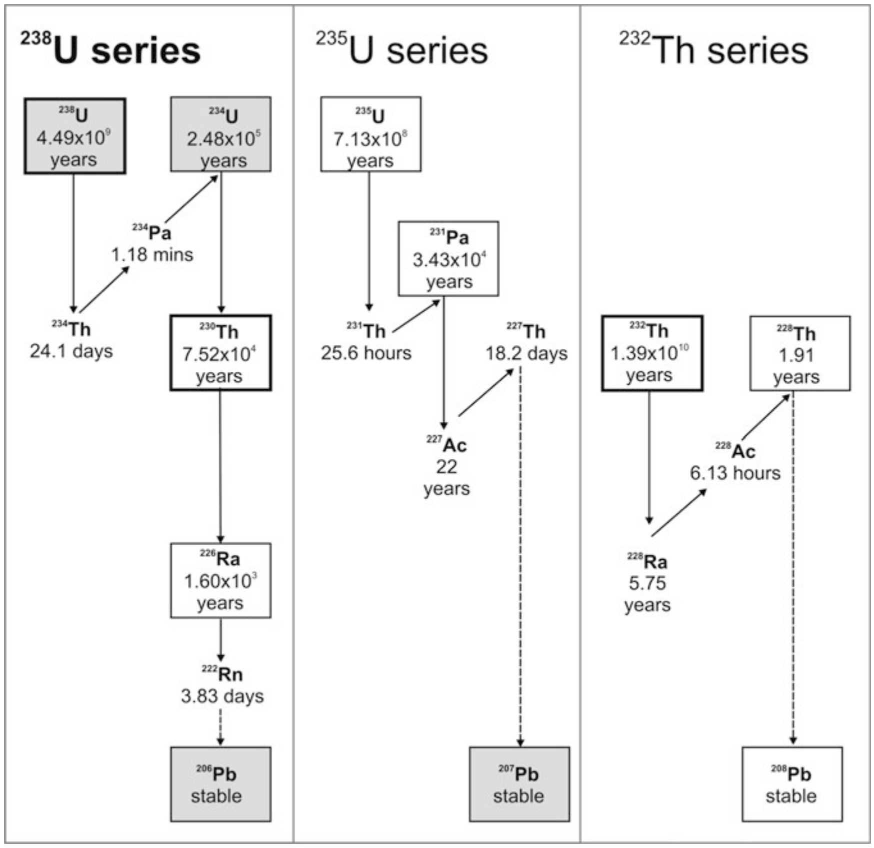
Essential concepts of U-series dating

The U-series decay chain contains radioactive isotopes of many elements, among them U, Th, Pa, and Ra, ending in stable Pb (Figure 1). In a closed system, the intermediate isotopes exist in so-called secular equilibrium, that is, their abundance ratios are such that each isotope decays at exactly the rate at which it is produced. Various natural processes cause the fractionation, or separation, of these elements, disturbing these equilibria among the isotopes. The gradual return to equilibrium conditions allows for a quantification of the time passed since the fractionation-causing event. In other words, the event that disturbed the equilibrium state of the isotopes, such as formation of a speleothem, can be dated by determining the extent to which the isotopes have reestablished equilibrium.

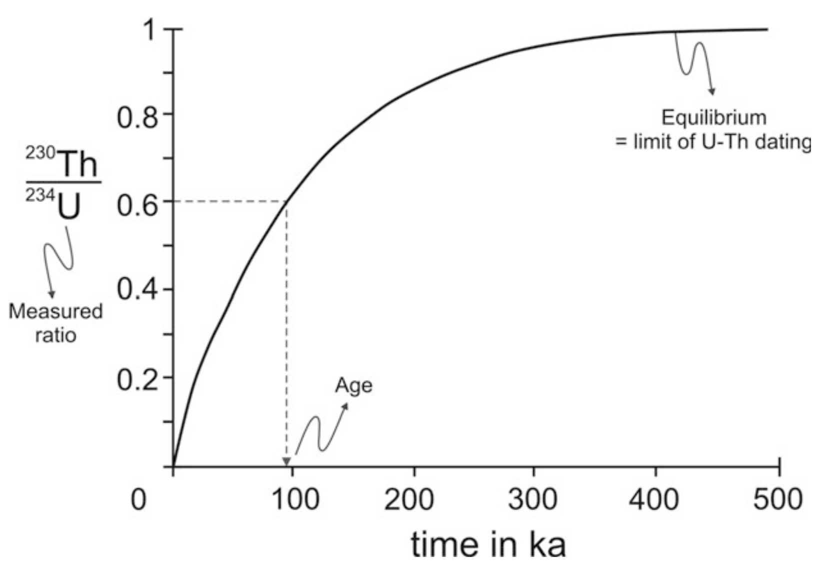
The most common process responsible for the fractionation of the isotopes in the U-series decay chain is the huge difference in solubility between U and Th. U is highly soluble in natural waters, while Th is not. For example, cave-drip waters are rich in U but almost devoid of Th; the stalagmite calcite formed from these waters therefore contains a few parts per million of U, with negligible amounts of Th. The subsequent in situ decay of ^{234}U to ^{230}Th, with a half-life of 245,000 years, can be used to date the material by measuring the present levels of both isotopes (Bourdon et al., 2003) (Figure 2). This U-Th dating method is inherently suitable to carbonate material, such as coral and cave carbonates or speleothems, as these develop from natural, U-rich, Th-poor waters.

However, ^{230}Th is itself radioactive, with a half-life of 75,000 years, so instead of accumulating indefinitely (as is the case for the U-Pb system), it instead approaches secular equilibrium with its parent isotope (Figure 2). This gives the U-Th dating system an upper age limit of around 500,000 years. With advances in mass spectrometry, corals as old as 600 ka can be dated (Andersen et al., 2008), with the other end of the datable age spectrum as young as a few thousand years (Cobb et al., 2003).

The U-series decay chain continues on beyond ^{230}Th and ends in stable ^{206}Pb, with a half-life of 4.47 billion



U-Series Dating, Figure 1 A schematic diagram of the U-series decay chains of ^{238}U, ^{235}U, and ^{232}Th. Isotopes involved in U-Th dating are shown in *bolded boxes*, while isotopes used in U-Pb dating are in *grey shaded boxes* (Image redrawn and modified from Walker, 2005).



U-Series Dating, Figure 2 A graph of the ratio of the radioactivity of ^{230}Th to that of its parent isotope ^{234}U as a function of time. If the initial $^{230}Th/^{234}U$ ratio is zero, then the age (x axis) can be read from this chart using the present, measured $^{230}Th/^{234}U$ ratio (y axis). As the $^{230}Th/^{234}U$ ratio approaches 1, the curve flattens out, producing infinite ages and an effective upper limit for U-Th dating (Redrawn and modified from Schwarcz, 1992).

years (Grenthe et al., 2011), meaning that U-Pb dating is easily suitable for materials belonging to long geological time scales, including the age of the Earth itself (Patterson, 1956). In fact, the challenge of U-Pb dating is applying it to “young” material only a few million years old and to even younger archaeological time scales. At present, U-Pb dating of younger material is restricted to rocks such as carbonates (Rasbury and Cole, 2009), including cave carbonates or speleothems (Woodhead et al., 2006). The advantage of U-Pb dating is that it covers the time period earlier than ~500 ka and picks up where U-Th dating and other Quaternary methods, such as OSL (optically stimulated luminescence), leave off. U-Pb dating of speleothems is a rapidly growing field that is already beginning to make an impact in areas like human evolution (e.g., Pickering et al., 2011a).

The simplest but essential prerequisite for successful U-series (as in U-Th and U-Pb) dating is that the material being dated has acted as a “closed system” (Walker, 2005). This means that since the time of formation, there can be no loss or gain of isotopes. If such a closed system can be achieved, then it is safe to assume that the measured Th in a sample is solely the product of the in situ decay of U. Most carbonates, corals, and speleothems fulfill this requirement, making them good candidates for U-series dating. Biological carbonates, such as bone, teeth, and shell, do not behave as a closed system but rather as “open systems,” with isotopes moving in and out of material post-deposition. In archaeological settings, material such as coral and speleothem may be rare, while bones, teeth, and shells are abundant, so much effort has gone into modeling the open-system behavior of buried bone (Hedges and Millard, 1995; Pike et al., 2002).

Laboratory techniques and advances

In order to undertake U-series dating, the isotopes of interest need to be isolated and concentrated from the bulk sample material. This is achieved through isotope dilution (Faure, 1977), often accomplished through ion-exchange chromatography. Once separated, these isotopes must be measured with the highest possible precision. The original measuring technique was alpha spectrometry, which relied on the alpha-emitting characteristic of ^{238}U as it decays. Very thin (one atom thick) layers of isotopes are placed in the alpha spectrometer, and as alpha particles are emitted, the alpha detectors produce electronic signals that generate a digital spectrum equivalent to the energy of the alpha particles. Tabulating counts vs. energy of the sample produces an alpha spectrum from which the isotopes of interest can be identified and quantified (Smart, 1991; Schwarcz, 1992; Latham, 2001; Goldstein and Stirling, 2003). Using this method, a single U-Th measurement usually takes a few days (Latham, 2001); even with over 10,000 counts, 1σ age errors for each isotope are at best 1 % and usually between 5 % and 10 % (Smart, 1991).

The 1980s saw one of the most significant advances in U-series dating with the rise of mass spectrometer analysis, whereby individual atoms are counted, as opposed to the less abundant alpha particles (for a detailed review, see Goldstein and Stirling, 2003). The mass spectrometer of choice at the time was a thermal ionizing mass spectrometer or TIMS. TIMS had a revolutionary effect on U-series dating; sample sizes and analytical errors dropped considerably, and the precision of age determinations increased (Chen et al., 1986; Edwards et al., 1987). Analysis time was also reduced from a week to several hours, meaning the number of samples analyzed increased substantially (Goldstein and Stirling, 2003). This method was initially developed for corals. The much more precise ages obtainable meant that corals as old as ~120,000 years could be dated, so for the first time, links between past sea levels and Milankovitch forcing could be made with conviction (Edwards et al., 1987). This method spread swiftly and was soon adapted for dating terrestrial carbonates, such as cave carbonates or speleothems, including stalagmites and flowstones (Li et al., 1989). Once dated, these deposits could be analyzed for the paleoenvironmental data contained within them, and the field of stalagmite studies grew rapidly.

The most recent advance in U-series dating is linked to the development of inductively coupled plasma mass spectrometry (ICP-MS). There are major advantages to this method, making it the dominant one for measuring U-series isotopes (Goldstein and Stirling, 2003). The high temperatures achieved in the plasma (~6,000 K) produce ionization efficiencies of >90 % for nearly all elements, and the signal intensity can be easily increased by using a more concentrated solution. Mass bias can be easily corrected for, and sample throughput is typically faster than for TIMS (Goldstein and Stirling, 2003). Multicollector ICP-MS is even more powerful, as multiple isotopes can be measured simultaneously, leading to very precise ages. For a more detailed discussion, see Goldstein and Stirling (2003).

An alternative to isotope dilution techniques is in situ measurements using laser ablation ICP-MS. Eggins et al. (2005) explored the potential of this method and found that dating could be successfully undertaken on samples as small as 100 μm and with U concentrations as low as 1 ppm. Another advantage of this approach is that U and Th concentrations, as well as U-series isotope ratios, can be continuously profiled along a sample, which is especially useful when trying to date bones, teeth, or shells (Eggins et al., 2005; Duval et al., 2011). Laser ablation can also be used to rapidly characterize, screen, and select suitable material from which dates can be obtained using conventional isotope dilution methods (Eggins et al., 2005). Although the amount of material consumed during laser ablation is negligible and the preparation of samples straightforward (Eggins et al., 2005), larger specimens such as stalagmites have to be cut up into ~10 cm slabs, which can be very destructive. An alternative to this is the use of a passive imaging technique, such as phosphor imaging, to create a "map" of the areas of higher radiation, assumed to be U rich, in the sample material prior to dating (Cole et al., 2003; Pickering et al., 2010).

Potential problem areas

The two major problem areas with U-series dating as it is applied to geoarchaeology are (1) the context of the dated material and (2) the suitability and purity of the material being dated. The chronostratigraphic relevance of the dated material to the fossils or archaeological deposits is one of the most common, and also most easily avoided, problems. If a flowstone layer underlies an archaeological deposit, it provides a maximum age (*terminus post quem*) for the deposits. Similarly, if a flowstone overlies a deposit, it provides a minimum age (*terminus ante quem*). However, many thousands to tens of thousands of years may be left unrecorded between the formation of the flowstone and deposition of the archaeological sediments. Ideally, if flowstone layers occur both above and below the deposits, then U-series ages for these layers can be used to infer the age of the deposits sandwiched between them. These circumstances, however, are rare, so the importance of understanding the local geology, site formation processes, stratigraphy of a deposit, and relationships between the dated layers and archaeological deposits, cannot be overstated.

Another frequently encountered problem is the suitability of the material of interest for dating. As already outlined above, speleothems (stalagmites and flowstones) make the best targets for U-series dating because they behave as a closed system. However, materials of greater interest to archaeologists, such as fossil bones, teeth, and shell, are often inherently unsuitable for U-series dating because these organic materials are subject to postmortem open-system behavior. Both uranium and thorium isotopes are mobile, and their uptake and loss needs to be modeled (Hedges and Millard, 1995; Pike et al., 2002; Pike and Pettitt, 2003). One possibility is to use in situ laser ablation to create profiles along material such as bones, teeth, and possibly mollusks to map out the patterns of U migration (Eggins et al., 2005). This approach has also been attempted using the U-Pb system on fossil tooth enamel from the early human (hominin)-bearing cave site of Swartkrans in South Africa (Balter et al., 2008). Again, the problem is that the post-deposition U loss has to be modeled, leading to ages with large uncertainties.

Even material well suited to U-series dating may suffer from contamination, however. The most common contamination is of the daughter isotopes, where some non-radiogenic isotopes are also incorporated into the material at the time of formation, adding to the daughter isotopes that are entirely of radiogenic origin (Walker, 2005). For U-Th dating, the ^{232}Th/^{230}Th ratio can be used as a measure of contamination of ^{230}Th from detrital material, such as dust, clay, or silt. ^{232}Th is not part of the ^{238}U decay chain used in U-Th dating (see Figure 1); it does not occur in pure calcite but does occur in detrital material, so its presence signifies detrital contamination, and the ratio of ^{232}Th/^{230}Th can be used to correct for this (Walker, 2005). This correction is usually made by constructing an isochron (Schwarcz and Latham, 1989). In the U-Pb dating scheme, radiogenic ^{206}Pb can be completely obscured by common ^{206}Pb, meaning that all age calculations are done by multiple sample analysis and isochron construction (Richards et al., 1998; Woodhead et al., 2006). A major issue in U-Pb dating of speleothem material is the initial ^{234}U/^{238}U ratio, both in how this is quantified (measured directly or modeled) and also how this ratio is taken into account in the U-Pb age calculations (Richards et al., 1998; Woodhead et al., 2006; Pickering et al., 2010). Without taking the initial excess of ^{234}U into account, ages are often greatly overestimated.

Examples of geoarchaeological applications

U-Th-dated speleothems associated with fossils and/or artifacts

U-series dating is best applied to speleothems, and their utility for dating archaeological sites has long been recognized (Schwarcz et al., 1979). In an early study at the cave site of La Chaise-de-Vouthon in France, U-Th dating was used to constrain the age of Lower to Middle Paleolithic artifacts and several Neanderthal fossils (Blackwell et al., 1983). The caves at La Chaise-de-Vouthon contain sedimentary deposits including numerous hominin fossils. Flowstone layers are interstratified with the fossil-bearing sediments, and these were dated using alpha spectrometry, providing a range of ages from $245 + 45/-28$ to 97 ± 6 ka and forming the chronology for the sequence. The hominin remains, in this case Neanderthals, consist mainly of fossil teeth that are found in the layers older than 101 ka (Blackwell et al., 1983).

The field of paleoanthropology was shaken up forever in 2004 by the discovery of a small, ~1 m tall hominin fossil nicknamed "The Hobbit" and known formally as *Homo floresiensis*, after the island of Flores where it was found (Brown et al., 2004). Knowing the age of the fossils is key to their interpretation. The deposits of Liang Bua cave have been thoroughly dated using ^{14}C, OSL, ESR (electron spin resonance), and U-series, with fossils and archaeological artifacts recovered from deposits spanning the interval of 95–12 ka (Morwood et al., 2004; Morwood et al., 2005; Roberts et al., 2009).

The cave sites along the Southern Cape coast in South Africa at the site of Pinnacle Point are an example of where U-Th dating of flowstones, coupled with OSL dating of archaeological sediments, has provided valuable age information (Marean et al., 2007). The oldest appearance of modern human behavior, evidenced in the systematic exploitation of marine resources, use of pigment, and production of bladelet stone tool technology, is dated to 164 ± 12 ka at these sites (Marean et al., 2007). The oldest known controlled use of fire, seen in the heat treatment of stone tools, is also documented at Pinnacle Point (Brown et al., 2009).

An alternative to dating flowstone layers, especially when these are absent from the deposits of interest, is to date buried speleothem material, such as buried soda straws, or tubular stalactites (St Pierre et al., 2012). Straws are so fragile that they cannot survive reworking, so their presence suggests rapid burial, and they can thus provide ages close to the time of sedimentation. This approach has been tested at Blanche Cave in South Australia (St Pierre et al., 2012).

U-Th dating rock art

In rare cases, speleothem deposits are directly associated with rock art and can be used to constrain the age of the paintings. This approach is most effective when the paintings are both under- and overlain by flowstone layers. By nature, such flowstones are prone to detrital contamination, so ages must be calculated via isochrons. Direct dating of rock art is complicated, and results must be interpreted with caution (Pettitt and Pike, 2007). One example is from China, where paintings in the Jinsha River area of northwest Yunnan Province have been dated to between 5,738 and 2,050 years old, and the older paintings are shown to be at least 3,400 years old (Taçon et al., 2012). It is also possible to date rock engravings using the same method by dating a thin flowstone layer covering them. Such an approach was used to date the oldest known rock art in Britain, where engravings at Creswell Crags were dated to 12,800 years BP (Pike et al., 2005).

U-Th dating organic material

As mentioned above, U-Th and U-Pb dating of organic material, such as bones and teeth, is particularly useful in geoarchaeology because these are primary archaeological materials (Pike and Pettitt, 2003). However, bones and teeth are also inherently open-system materials, and the need to model this behavior often leads to ages with considerable errors.

There is a long history of using U-Th to date fossil bone from China, where the bones are very well preserved by mineral salts in solution percolating through the deposits, leading to permineralization. While there has been some success in dating the fossils, the best results are obtained by also dating flowstones intercalated with the deposits (Shen et al., 2001). These authors provide ages of between 400 and 500 ka for the "Peking Man" (*Homo erectus*) fossils from the Zhoukoudian Cave site, southwest of Beijing. These U-Th ages imply that human occupation of the Zhoukoudian site occurred much earlier and lasted much longer than previously thought.

A recent example of U-Th dating of bone is at the site of Cova del Gegant in Spain, where a range of dating techniques has been used to constrain the age of the deposits, along with careful work on the stratigraphy and history of sedimentary infilling of the cave (Daura et al., 2010). The deposits themselves are dated to 49.3 ± 1.8 ka, based on the U-Th age of the capping flowstone, and 60.0 ± 3.9 ka, based on the OSL of basal sediments. The U-Th age on the Neanderthal mandible itself falls neatly within this bracket at 52.3 ± 2.3 ka (Daura et al., 2010). Further examples and a discussion of the problems associated with U-series dating of bone are detailed in Pike and Pettitt (2003). U-series dating can also be used in conjunction with ESR dating of fossil tooth enamel and dentine. The Banyoles mandible, from Girona, Spain, anatomically appears to be pre-Neanderthal but is encased in travertine dated to ~45 ka, by which time pre-Neanderthals were thought to be extinct in this region for over 100 ka. Combined U-series and ESR dates give an age of 66 ± 7 ka (Grün et al., 2006), which is still younger than expected, thus highlighting the importance of the context of the fossil and the variation in the Neanderthal fossil record.

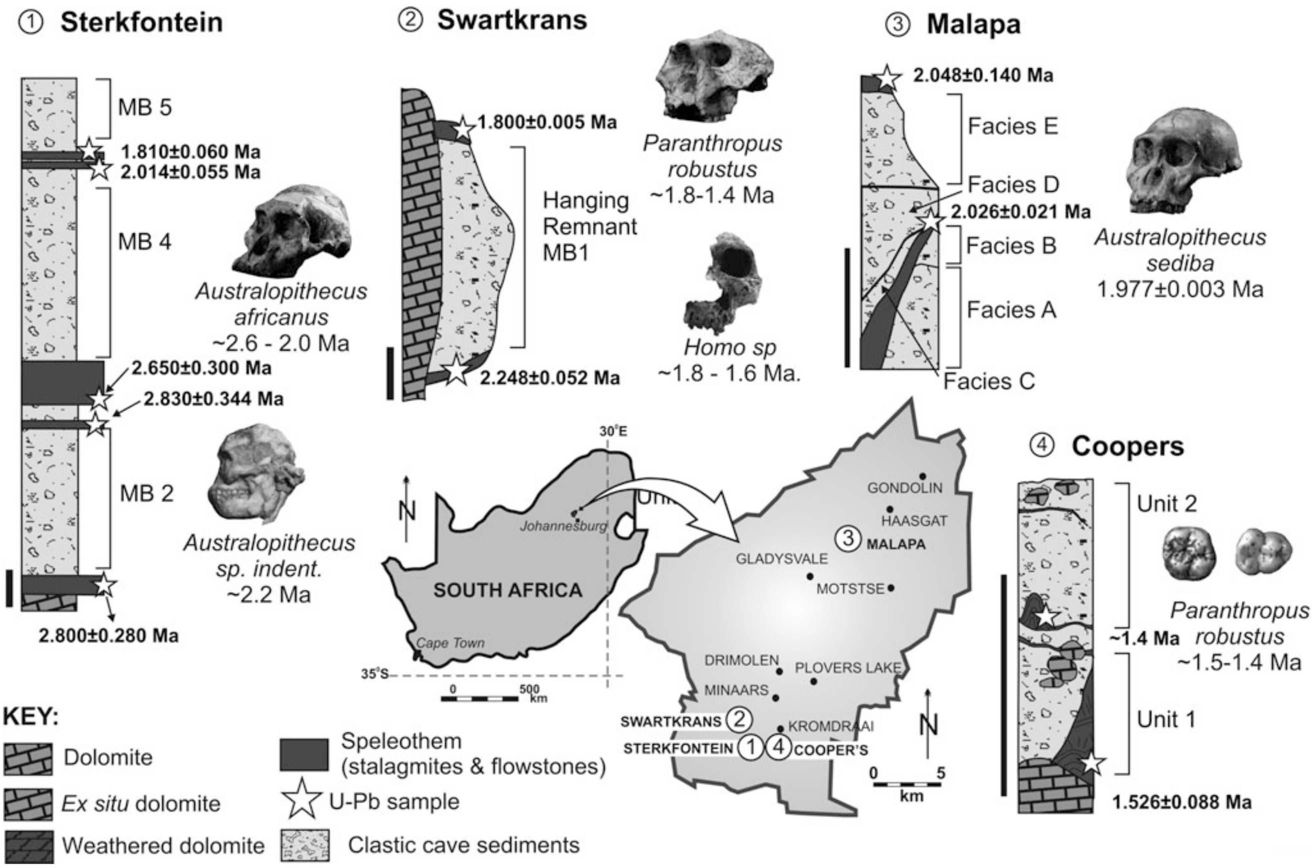
An exciting possible alternative to dating bone or teeth is dating buried wood. A method for this has been successfully applied to buried wood of pre-Holocene age from sediment sequences along the Hudson Bay lowlands in Canada (Allard et al., 2012) and could have many applications in archaeological settings.

U-Th-dated speleothems as records of paleoclimate

Ages from flowstones and stalagmites not directly associated with archaeological deposits are still of interest and can inform on the life history of the caves, their cycles of opening and closing, and their availability for occupation, such as at the Naracoorte Caves in South Australia (Ayliffe and Veer, 1988; Moriarty et al., 2000). The carbon and oxygen isotope records from such speleothem material can also be used to infer past climates and provide the paleo-environmental context for the archaeological deposits, such as at the Pinnacle Point caves in South Africa (Bar-Matthews et al., 2010) and at the *Homo floresiensis* site of Liang Bua on the island of Flores (Westaway et al., 2009).

U-Pb dating of flowstone applied to early hominins

The series of dolomite-hosted caves in the region known as the "Cradle of Humankind" are the richest source of hominin fossils outside East Africa: at least four species of hominin are represented, as well as an abundant fossil fauna. These caves provide ideal targets for the recently developed U-Pb techniques (Pickering et al., 2010): while the cave sediments themselves are complex and not simple layer-cake deposits, flowstone layers are ubiquitous. U-Pb ages for flowstone layers from above and below the major hominin-bearing sediment layers from three of the most important sites – Sterkfontein, Swartkrans, and Coopers – provide broad age ranges for these deposits between ~2.8 and ~1.4 Ma (see Figure 3) (de Ruiter et al., 2009; Pickering and Kramers, 2010; Pickering et al., 2011a; Pickering et al., 2011b), as well as an age of



U-Series Dating, Figure 3 A summary diagram of the cave sites in the "Cradle of Humankind," South Africa, showing the location of these caves, their stratigraphy, the position and age of U-Pb-dated flowstones, and the corresponding ages for the early hominin fossils from each site (Data taken from Walker et al., 2006; de Ruiter et al., 2009; Dirks et al., 2010; Pickering and Kramers, 2010; Pickering et al., 2010; Pickering et al., 2011a; Pickering et al., 2011b).

~2.2 Ma for the flowstones surrounding the "Little Foot" fossil (StW 573) at Sterkfontein Cave (Walker et al., 2006). At present, the U-Pb age ranges are necessarily broad. However, if combined with the paleomagnetic signal preserved in the flowstones and sediments surrounding the actual fossils, much narrower time ranges can be obtained, such as for *Australopithecus sediba* (Pickering et al., 2011a).

Summary

The contribution of U-series dating to Quaternary science in general and geoarchaeology in particular has been considerable. The presence of an alternative chronometer to ^{14}C dating and OSL, reaching back in time well beyond the cutoff for both these methods, is a welcome addition to the field. U-series dating has benefitted from advances in mass spectrometry, and today, large volumes of precise ages can be easily and quickly obtained. Carbonates are best suited to U-series dating, and the ability of U-series to provide both accurate and precise ages on speleothem material is particularly useful in dating cave deposits containing fossils or archaeological remains. This is especially pertinent because caves, functioning either as occupation sites or receptacles for surface material being washed in, provide an environment with potentially high preservation. As such, U-Th, and more recently U-Pb, has had a significant impact on dating early human or hominin fossils. Research into directly dating fossil material, i.e., bones and teeth, is ongoing. The most important aspect of using U-Th dating in geoarchaeology is the context of the dated material and how this relates to the fossils or artifacts of interest.

Bibliography

Allard, G., Roy, M., Ghaleb, B., Richard, P. J. H., Larouche, A. C., Veillette, J. J., and Parent, M., 2012. Constraining the age of the last interglacial-glacial transition in the Hudson Bay lowlands (Canada) using U-Th dating of buried wood. *Quaternary Geochronology*, **7**, 37–47.

Andersen, M. B., Stirling, C. H., Potter, E.-K., Halliday, A. N., Blake, S. G., McCulloch, M. T., Ayling, B. F., and O'Leary, M., 2008. High-precision U-series measurements of more than 500,000 year old fossil corals. *Earth and Planetary Science Letters*, **265**(1–2), 229–245.

Ayliffe, L. K., and Veer, H. H., 1988. Uranium-series dating of speleothems and bones from Victoria Cave, Naracoorte, South Australia. *Chemical Geology: Isotope Geoscience Section*, **72**(3), 211–234.

Balter, V., Blichert-Toft, J., Braga, J., Telouk, P., Thackeray, F., and Albarède, F., 2008. U-Pb dating of fossil enamel from the Swartkrans Pleistocene hominid site, South Africa. *Earth and Planetary Science Letters*, **267**(1–2), 236–246.

Bar-Matthews, M., Marean, C. W., Jacobs, Z., Karkanas, P., Fisher, E. C., Herries, A. I. R., Brown, K., Williams, H. M., Bernatchez, J., Ayalon, A., and Nilssen, P. J., 2010. A high resolution and continuous isotopic speleothem record of paleoclimate and paleoenvironment from 90 to 53 ka from Pinnacle Point on the south coast of South Africa. *Quaternary Science Reviews*, **29** (17–18), 2131–2145.

Blackwell, B., Schwarcz, H. P., and Debénath, A., 1983. Absolute dating of hominids and palaeolithic artifacts of the cave of La Chaise-de-Vouthon (Charente), France. *Journal of Archaeological Science*, **10**(6), 493–513.

Bourdon, B., Henderson, G. M., Lundstrom, C. C., and Turner, S. (eds.), 2003. *Uranium-Series Geochemistry*. Washington: Mineralogical Society of America. Reviews in Mineralogy and Geochemistry, Vol. 52.

Brown, P., Sutikna, T., Morwood, M. J., Soejono, R. P., Jatmiko, Saptomo, E. W., and Due, R. A., 2004. A new small-bodied hominin from the Late Pleistocene of Flores, Indonesia. *Nature*, **431**(7012), 1055–1061.

Brown, K. S., Marean, C. W., Herries, A. I. R., Jacobs, Z., Tribolo, C., Braun, D., Roberts, D. L., Meyer, M. C., and Bernatchez, J., 2009. Fire as an engineering tool of early modern humans. *Science*, **325**(5942), 859–862.

Chen, J. H., Edwards, R. L., and Wasserburg, G. J., 1986. ^{238}U, ^{234}U and ^{232}Th in seawater. *Earth and Planetary Science Letters*, **80** (3–4), 241–251.

Cobb, K. M., Charles, C. D., Cheng, H., and Edwards, R. L., 2003. El Niño/Southern Oscillation and tropical Pacific climate during the last millennium. *Nature*, **424**(6946), 271–276.

Cole, J. M., Nienstedt, J., Spataro, G., Rasbury, E. T., Lanzirotti, A., Celestian, A. J., Nilsson, M., and Hanson, G. N., 2003. Phosphor imaging as a tool for in situ mapping of ppm levels of uranium and thorium in rocks and minerals. *Chemical Geology*, **193** (1–2), 127–136.

Daura, J., Sanz, M., Pike, A. W. G., Subirà, M. E., Fornós, J. J., Fullola Pericot, J. M., Julià, R., and Zilhão, J., 2010. Stratigraphic context and direct dating of the Neanderthal mandible from Cova del Gegant (Sitges, Barcelona). *Journal of Human Evolution*, **59**(1), 109–122.

de Ruiter, D. J., Pickering, R., Steininger, C. M., Kramers, J. D., Hancox, P. J., Churchill, S. E., Berger, L. R., and Backwell, L., 2009. New *Australopithecus robustus* fossils and associated U-Pb dates from Cooper's Cave (Gauteng, South Africa). *Journal Of Human Evolution*, **56**(5), 497–513.

Dirks, P. H. G. M., Kibii, J. M., Kuhn, B. F., Steininger, C., Churchill, S. E., Kramers, J. D., Pickering, R., Farber, D. L., Mériaux, A.-S., Herries, A. I. R., King, G. C. P., and Berger, L. R., 2010. Geological setting and age of *Australopithecus sediba* from Southern Africa. *Science*, **328**(5975), 205–208.

Duval, M., Aubert, M., Hellstrom, J., and Grün, R., 2011. High resolution LA-ICP-MS mapping of U and Th isotopes in an early Pleistocene equid tooth from Fuente Nueva-3 (Orce, Andalusia, Spain). *Quaternary Geochronology*, **6**(5), 458–467.

Edwards, R. L., Chen, J. H., and Wasserburg, G. J., 1987. ^{238}U—^{234}U—^{230}Th—^{232}Th systematics and the precise measurement of time over the past 500,000 years. *Earth and Planetary Science Letters*, **81**(2–3), 175–192.

Eggins, S. M., Grün, R., McCulloch, M. T., Pike, A. W. G., Chappell, J., Kinsley, L., Mortimer, G., Shelley, M., Murray-Wallace, C. V., Spötl, C., and Taylor, L., 2005. In situ U-series dating by laser-ablation multi-collector ICPMS: new prospects for Quaternary geochronology. *Quaternary Science Reviews*, **24**(23–24), 2523–2538.

Faure, G., 1977. *Principles of Isotope Geology*. New York: Wiley.

Goldstein, S. J., and Stirling, C. H., 2003. Techniques for measuring uranium-series nuclides: 1992–2002. In Bourdon, B., Henderson, G. M., Lundstrom, C. C., and Turner, S. (eds.), *Uranium-Series Geochemistry*. Washington: Mineralogical Society of America. Reviews in Mineralogy and Geochemistry, Vol. 52, pp. 23–57.

Grenthe, I., Drożdżyński, J., Fujino, T., Buck, E. C., Albrecht-Schmitt, T. E., and Wolf, S. F., 2011. Chapter 5. Uranium. In Morss, L. R., Edelstein, N. M., and Fuger, J. (eds.), *Chemistry of the Actinide and Transactinide Elements*, 4th edn. Dordrecht: Springer, Vol. 1, pp. 253–698.

Grün, R., Maroto, J., Eggins, S., Stringer, C., Robertson, S., Taylor, L., Mortimer, G., and McCulloch, M., 2006. ESR and U-series analyses of enamel and dentine fragments of the Banyoles mandible. *Journal of Human Evolution*, **50**(3), 347–358.

Hedges, R. E. M., and Millard, A. R., 1995. Bones and groundwater: towards the modelling of diagenetic processes. *Journal of Archaeological Science*, **22**(2), 155–164.

Ivanovich, M., and Harmon, R. S., 1992. *Uranium-series Disequilibrium: Applications to Earth, Marine and Environmental Science*, 2nd edn. Oxford: Clarendon Press.

Latham, A. G., 2001. Uranium-series dating. In Brothwell, D. R., and Pollard, A. M. (eds.), *Handbook of Archaeological Sciences*. Chichester/New York: Wiley Interscience, pp. 63–72.

Li, W.-X., Lundberg, J., Dickin, A. P., Ford, D. C., Schwarcz, H. P., McNutt, R., and Williams, D., 1989. High-precision mass-spectrometric uranium-series dating of cave deposits and implications for palaeoclimate studies. *Nature*, **339**(6225), 534–536.

Marean, C. W., Bar-Matthews, M., Bernatchez, J., Fisher, E., Goldberg, P., Herries, A. I. R., Jacobs, Z., Jerardino, A., Karkanas, P., Minichillo, T., Nilssen, P. J., Thompson, E., Watts, I., and Williams, H. M., 2007. Early human use of marine resources and pigment in South Africa during the Middle Pleistocene. *Nature*, **449**(7164), 905–908.

Moriarty, K. C., McCulloch, M. T., Wells, R. T., and McDowell, M. C., 2000. Mid-Pleistocene cave fills, megafaunal remains and climate change at Naracoorte, South Australia: towards a predictive model using U-Th dating of speleothems. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **159** (1–2), 113–143.

Morwood, M. J., Soejono, R. P., Roberts, R. G., Sutikna, T., Turney, C. S. M., Westaway, K. E., Rink, W. J., Zhao, J.-X., van den Bergh, G. D., Due, R. A., Hobbs, D. R., Moore, M. W., Bird, M. I., and Fifield, L. K., 2004. Archaeology and age of a new hominin from Flores in eastern Indonesia. *Nature*, **431**(7012), 1087–1091.

Morwood, M. J., Brown, P., Jatmiko, Sutikna, T., Saptomo, E. W., Westaway, K. E., Due, R. A., Roberts, R. G., Maeda, T., Wasisto, S., and Djubiantono, T., 2005. Further evidence for small-bodied hominins from the Late Pleistocene of Flores, Indonesia. *Nature*, **437**(7061), 1012–1017.

Patterson, C., 1956. Age of meteorites and the earth. *Geochimica et Cosmochimica Acta*, **10**(4), 230–237.

Pettitt, P., and Pike, A., 2007. Dating European palaeolithic cave art: progress, prospects, problems. *Journal of Archaeological Method and Theory*, **14**(1), 27–47.

Pickering, R., and Kramers, J. D., 2010. Re-appraisal of the stratigraphy and new U-Pb dates for the Sterkfontein hominin site, South Africa. *Journal of Human Evolution*, **59**(1), 70–86.
Pickering, R., Kramers, J. D., Partridge, T. C. P., Kodolanyi, J., and Pettke, T., 2010. U–Pb dating of calcite–aragonite layers in speleothems from hominin sites in South Africa by MC-ICP-MS. *Quaternary Geochronology*, **5**(5), 544–558.
Pickering, R., Dirks, P. H. G. M., Jinnah, Z., de Ruiter, D. J., Churchill, S. E., Herries, A. I. R., Woodhead, J. D., Hellstrom, J. C., and Berger, L. R., 2011a. *Australopithecus sediba* at 1.977 Ma and implications for the origins of the genus *Homo. Science*, **333**(6048), 1421–1423.
Pickering, R., Kramers, J. D., Hancox, P. J., de Ruiter, D. J., and Woodhead, J. D., 2011b. Contemporary flowstone development links early hominin bearing cave deposits in South Africa. *Earth and Planetary Science Letters*, **306**(1–2), 23–32.
Pike, A. W. G., and Pettitt, P. B., 2003. U-series dating and human evolution. In Bourdon, B., Henderson, G. M., Lundstrom, C. C., and Turner, S. (eds.), *Uranium-Series Geochemistry.* Washington: Mineralogical Society of America. Reviews in Mineralogy and Geochemistry, Vol. 52, pp. 607–630.
Pike, A. W. G., Hedges, R. E. M., and van Calsteren, P., 2002. U-series dating of bone using the diffusion-adsorption model. *Geochimica et Cosmochimica Acta*, **66**(24), 4273–4286.
Pike, A. W. G., Gilmour, M., Pettitt, P., Jacobi, R., Ripoll, S., Bahn, P., and Muñoz, F., 2005. Verification of the age of the Palaeolithic cave art at Creswell Crags, UK. *Journal of Archaeological Science*, **32**(11), 1649–1655.
Rasbury, E. T., and Cole, J. M., 2009. Directly dating geologic events: U-Pb dating of carbonates. *Reviews of Geophysics*, **47**(3), RG3001, doi:10.1029/2007RG000246.
Richards, D. A., Bottrell, S. H., Cliff, R. A., Ströhle, K., and Rowe, P. J., 1998. U-Pb dating of a speleothem of Quaternary age. *Geochimica et Cosmochimica Acta*, **62**(23–24), 3683–3688.
Roberts, R. G., Westaway, K. E., Zhao, J.-X., Turney, C. S. M., Bird, M. I., Rink, W. J., and Fifield, L. K., 2009. Geochronology of cave deposits at Liang Bua and of adjacent river terraces in the Wae Racang valley, western Flores, Indonesia: a synthesis of age estimates for the type locality of *Homo floresiensis. Journal of Human Evolution*, **57**(5), 484–502.
Schwarcz, H. P., 1989. Uranium series dating of Quaternary deposits. *Quaternary International*, **1**, 7–17.
Schwarcz, H. P., 1992. Uranium-series dating and the origin of modern man. *Philosophical Transactions: Biological Sciences*, **337**(1280), 131–137.
Schwarcz, H. P., and Latham, A. G., 1989. Dirty calcites 1. - Uranium-series dating of contaminated calcite using leachates alone. *Chemical Geology: Isotope Geoscience Section*, **80**(1), 35–43.
Schwarcz, H. P., Blackwell, B., Goldberg, P., and Marks, A. E., 1979. Uranium series dating of travertine from archaeological sites, Nahal Zin, Israel. *Nature*, **277**(5697), 558–560.
Shen, G., Ku, T.-L., Cheng, H., Edwards, R. L., Yuan, Z., and Wang, Q., 2001. High-precision U-series dating of Locality 1 at Zhoukoudian, China. *Journal of Human Evolution*, **41**(6), 679–688.
Smart, P. L., 1991. Uranium series dating. In Smart, P. L., and Frances, P. D. (eds.), *Quaternary Dating Methods: A User's Guide*. Cambridge, UK: Quaternary Research Association. Technical Guide, Vol. 4, pp. 45–83.
St Pierre, E., Zhao, J.-X., Feng, Y.-X., and Reed, E., 2012. U-series dating of soda straw stalactites from excavated deposits: method development and application to Blanche Cave, Naracoorte, South Australia. *Journal of Archaeological Science*, **39**(4), 922–930.
Taçon, P. S. C., Aubert, M., Gang, L., Decong, Y., Hong, L., May, S. K., Fallon, S., Xueping, J., Curnoe, D., and Herries, A. I. R., 2012. Uranium-series age estimates for rock art in southwest China. *Journal of Archaeological Science*, **39**(2), 492–499.
Walker, M. C. J., 2005. *Quaternary Dating Methods*. Chichester/New York: Wiley.
Walker, J., Cliff, R. A., and Latham, A. G., 2006. U-Pb isotopic age of the StW 573 hominid from Sterkfontein, South Africa. *Science*, **314**(5805), 1592–1594.
Westaway, K. E., Roberts, R. G., Sutikna, T., Morwood, M. J., Drysdale, R., Zhao, J.-X., and Chivas, A. R., 2009. The evolving landscape and climate of western Flores: an environmental context for the archaeological site of Liang Bua. *Journal of Human Evolution*, **57**(5), 450–464.
Woodhead, J., Hellstrom, J., Maas, R., Drysdale, R., Zanchetta, G., Devine, P., and Taylor, E., 2006. U-Pb geochronology of speleothems by MC-ICPMS. *Quaternary Geochronology*, **1**(3), 208–221.

Cross-references

Cave Settings
Chemical Alteration
Chronostratigraphy
Inductively Coupled Plasma-Mass Spectrometry (ICP-MS)
Isochron Dating
Liang Bua
Optically Stimulated Luminescence (OSL) Dating
Paleoenvironmental Reconstruction
Paleomagnetism
Pinnacle Point
Site Formation Processes
Speleothems
Sterkfontein/Swartkrans/Kromdraai
Zhoukoudian

V

VOLCANOES AND PEOPLE

Payson Sheets
Department of Anthropology, University of Colorado, Boulder, CO, USA

Introduction

Volcanoes and people have been interacting as long as people have been on earth, and those interactions include beneficial and detrimental aspects. Volcanic activity can provide useful resources, such as stone for building and tools, and parent material from which rich soils can develop. Eruptions can preserve settlements to an extraordinary degree, such as Pompeii, from which we can learn much about ancient peoples and cultures. Volcanic eruptions can have creative repercussions, as people learn about hazardous zones and recoveries, and they alter their locations of settlement and even their belief systems to accommodate to risks. Eruptions can also be destructive, causing many human injuries and deaths, devastation of natural habitats, or even the demise of societies.

Volcanic activity

The Smithsonian Institution provides a comprehensive worldwide website of volcanic eruptions that have occurred during the past few million years at: http://www.volcano.si.edu/index.cfm. Volcanoes can erupt effusively, with hot magma flowing in rivers such as those in Hawaii. They may fill in fertile valleys and take a long time to weather to cultivatable soils, but they rarely harm people directly. During explosive, or Plinian eruptions, volcanic ash and gases are blasted into the air from whence they fall and affect widespread areas, potentially causing significant human impacts. Volcanic ash weathers more rapidly than lava, and thin deposits can be beneficial to soils shortly after they fall to the ground. Volcanic ash deposits are sometimes mobilized by water saturation many years after the last eruptive event and flow as a lahar; this viscous slurry can move very rapidly depending on the slope, and they can fill valleys with devastating effect to everything in its path. A recent summary of the nature of volcanic eruptions also includes their effects as well as controversies about interpretations (Oppenheimer, 2011).

Volcanic eruptions and early human evolution

Our early ancestors of a few million years ago had occasional interactions with volcanoes. Footprints at Laetoli, Tanzania, are preserved in volcanic ash that dates to about 3.6 million years ago (Leakey, 1979). They demonstrate upright bipedal walking by early australopithecines. Olduvai Gorge, also in Tanzania, has yielded fossil bones and stone tools of australopithecines, *Homo habilis* and *Homo erectus*, over a two-million-year time span, dated as at Laetoli by radiometric techniques such as K-Ar and Ar-Ar on volcanic ash layers (Renfrew and Bahn, 2004, 152–153). The skeletons document biological evolution, and the stone tools show increasing sophistication from crude Oldowan pebble tools to sophisticated bifacially flaked implements.

Vesuvius volcano and Pompeii

The most famous interaction of people and volcanoes in ancient times is the eruption of Vesuvius which resulted in the burial of Pompeii and its sister city Herculaneum (Berry, 2007). Pompeii was a resort city for affluent Romans, with elegant public buildings including temples, theaters, baths, brothels, fora, and markets, along with many multistory residences, all encircled by high city walls. Many households engaged in crafts such as making bread. Many residences are decorated with painted murals that depict aspects of everyday life, feasting, and religious scenes. Public notices were painted on walls announcing

A.S. Gilbert (ed.), *Encyclopedia of Geoarchaeology*, DOI 10.1007/978-1-4020-4409-0,

festivals and political candidates. Graffiti included a wide range of personal matters.

Pompeii was buried by about 5 m of volcanic ash from Vesuvius volcano on 24 August AD 79. There were some warnings, such as strong earthquakes, and many residents fled the city. Evidently, some fled to Herculaneum, where they were eventually killed during the eruption by pyroclastic flows, swift-moving density currents of gases, and rock that flow downward and outward from the erupting volcano and sometimes reach temperatures over 1,000 °C. Hundreds of others remained in Pompeii and were killed, along with their animals, asphyxiated by gases and covered by ash and lapilli – larger pieces of congealed magma that fall with the ash. Apart from the misfortune of those killed and entombed, the volcanic ash preserved the city so well that we can learn much from it.

Pompeii was rediscovered in 1748, and for over a century it was "mined" for marble sculptures by underground tunneling with no recording of where recovered objects came from. The earliest archaeology dates to the 1860s with the work of Giuseppi Fiorelli. He devised the technique of filling with plaster of Paris the hollows left in the volcanic ash where a person had been encased and subsequently decomposed. Once the molds were revealed, the people could be seen in great anguish as they struggled to breathe and eventually died. Excavations have continued into the present, until almost the entire ancient city has been dug, representing the most extensive urban archaeology project in the world. The social, political, economic, and religious life of Romans, at about the apex of their civilization, are revealed by the careful excavations of the well-preserved remains.

Oppenheimer (2011, 111) notes the irony that the Vesuvius eruption that buried Pompeii and Herculaneum is the most famous volcanic-human interaction remembered today, yet it had very little impact on Roman civilization at the time. Probable reasons for its minimal impact include Pompeii's relatively small population, about 10,000 people, compared to the overall population of Rome's thriving and expanding empire, and the fact that the area devastated by Vesuvius was a tiny fraction of the total empire, and agricultural recovery was reasonably rapid in areas buried less deeply than was Pompeii.

The Thera eruption and Minoan civilization

Based on the large island of Crete, the Minoan civilization thrived in the eastern Mediterranean during the centuries from around 2500 BC to about 1500 BC (Doumas, 1983; Castleden, 1990). The civilization is known for elaborate palaces, elegant art in sculptures and wall paintings, and maritime trading all around the eastern Mediterranean. The Minoans produced high-quality wheel-thrown pottery, metal objects, ivory carvings, and other goods that were in high demand by other societies. The relatively thin dusting of volcanic ash from Thera arriving on Crete would not have caused great difficulties, but the tsunami generated by the eruption (Oppenheimer, 2011, 235) would have destroyed the fishing and trading fleets as well as warships.

Minoan civilization went into a decline, marked by the destruction by burning of palaces at about 1450 BC. Civil disorder was widespread, with internal conflict, abandonments of settlements, hoarding, and the emergence of religious "crisis cults" and even human sacrifice and cannibalism (Oppenheimer, 2011, 237). The demise of Minoan civilization allowed its land-based competitor, the Mycenaean civilization, to expand and thrive. As early as the 1930s, scholars suggested the cause of the decline was the eruption of Thera volcano. Located 110 km north of Crete, Thera, on the island now called Santorini, erupted violently and deeply buried a Minoan city called Akrotiri. The residents apparently had sufficient warning and evacuated, as no bodies have been found to date. The architectural preservation is much like at Pompeii, and the multistory buildings have beautiful murals depicting landscape scenes, men boxing, and religious themes. The volcanic destruction and excellent preservation of Akrotiri by the eruption is incontrovertible, but it remains controversial if that eruption was instrumental in the decline of Minoan civilization. Some have argued it was the sole cause for the decline, others propose that it was a contributing factor, and yet others claim that it was not connected. A key issue is whether the eruption and the collapse correspond in time. Initially thought to have occurred around 1500 BC, it is now suspected that the volcanic event happened earlier, with radiocarbon dates and possibly related climatic proxy evidence from other parts of the world suggesting a date around 1628 or at least in the late seventeenth century BC (Friedrich et al., 2006; Manning, 2014).

Highland central Mexico

Teotihuacán (Evans and Webster, 2001, 723–735) was the largest, most highly organized, and most influential city of the New World during the first millennium AD (Figure 1). It was affected three times by volcanic activity: twice early in its growth and once at its apex. The Xitle eruption (Siebe, 2000), about 2,000 years ago in the southern Basin of Mexico, devastated Cuicuilco, the largest polity in the area. Many refugees apparently went to Teotihuacán, contributing to its remarkable growth spurt at that time (Evans and Webster, 2001, 199). Popocatepetl volcano, on the west side of the basin, erupted a little more than 2,000 years ago (Siebe et al., 1996). Its eruption was many times greater than Xitle's and devastated productive lands to the east. Many refugees may also have gone to Teotihuacán and been part of its sudden population explosion. The city grew to be a regional power, with religious, social, and economic impacts throughout most of Mesoamerica even as far as Copan in Honduras.

The Popocatepetl eruption deposited volcanic ash over cornfields and households to the east, preserving them extraordinarily well (Plunket and Uruñuela, 1998).

Volcanoes and People, Figure 1 Teotihuacan was the largest ancient city in Mexico from about AD 100–550. The "Avenue of the Dead" runs north and south past many small pyramids, as well as the huge Pyramid of the Sun on the left. The wooden temples atop the small pyramids were deliberately burned when people lost faith in their religion around AD 550.

The households at Tetimpa were standardized, with multiple buildings facing a central patio. Each patio featured a volcano effigy shrine indicating anxiety about a future eruption and the use of supernatural means to mitigate or avoid it.

The demise of Teotihuacán is not well dated. It could have happened as early as the mid-sixth century or as late as the eighth century. The problem that produces this vagueness is a flattening of the radiocarbon calibration curve, which makes precise dating impossible. If the collapse occurred in the mid-sixth century, then it may well have been caused by a colossal volcanic eruption (see below).

The volcanically caused worldwide atmospheric phenomenon of AD 536

A dry fog dust cloud spread worldwide throughout the atmosphere in AD 536 and was recorded by historians in China, where the prolonged cold and drought caused by reduced solar radiation produced crop failures and the deaths of approximately 75 % of the people in a northern kingdom (Houston, 2000). Other authors in the same volume as Houston's chapter document similar crop failures, starvation, and social instabilities in Europe, North Africa, and the Near East, all beginning at AD 536 and continuing for many years. Larsen et al. (2008) document the most severe cold years of the past two millennia beginning in AD 536 as recorded in tree rings in the Northern Hemisphere. They also note strong sulfur spikes in ice cores in Greenland and Antarctica at the same time and conclude that the cause must have been a large explosive volcanic eruption near the equator. Dull et al. (2010) suggest the massive explosive eruption of Ilopango Caldera in El Salvador at 14° north of the equator probably was the cause. The eruption blasted some 84 km^3 of volcanic ash into the atmosphere, completely eliminating all living flora, fauna, and people in central and western El Salvador. The Miraflores branch of the Classic Maya civilization was completely devastated in that area and in adjoining Guatemala, and it was severely afflicted in its eastern extent around Kaminaljuyu (Guatemala City) (Dull et al., 2001). The eruption may have caused, or at least contributed to, the social disruptions in the Maya lowlands known as the "hiatus" in the sixth century (Robichaux, 2000). In any event, it was the greatest eruption during the last 84,000 years in Central America, and its impact on nearby societies echoed through the centuries. Presently, Ilopango Lake fills the volcanic crater (Figure 2a, b), which covers an area of 28 mi^2 (72 km^2) and lies at an elevation of just under 1,500 ft (450 m).

The Ilopango eruption was certainly the largest of a total of 36 cases of volcanic eruptions affecting ancient societies in Mexico and Central America being studied by Sheets (2001). Arenal volcano in northwestern Costa Rica erupted 10 times during the past 4,000 years (Figure 3), causing the abandonment of scores of villages and forcing the survivors to live in refuge areas until they could reoccupy their settlements. Only a small part of their diet came from domesticated foods (they lived off the abundance of wild foods in the tropical rainforest), and population densities were very low with no evidence of warfare, facilitating relocation to refuge areas. As their

Volcanoes and People, Figure 2 (**a**) Central El Salvador in Central America, with Lake Ilopango in the center. It was the source of the huge explosive eruption that evidently caused the worldwide climatic crisis of AD 536. The eruption occurred through the lake and caused a caldera. The Cerén archaeological site is located in the northwest corner of this image. From Google Maps, terrain view. (**b**) Aerial view of the west end of Lake Ilopango, the caldera formed by the Plinian eruption in the middle of the Maya Classic Period. All people, animals, and vegetation were killed in this area.

Volcanoes and People, Figure 3 Arenal Volcano in Costa Rica, with Lake Arenal in the foreground. Arenal erupted frequently in ancient times, and the egalitarian native peoples learned how to handle the emergencies very successfully.

Volcanoes and People, Figure 4 Bruce Dahlin clearing around a boulder with petroglyphs in the Barriles chiefdom's territory in Panama. The petroglyphs apparently functioned as boundary markers. Baru volcano is in the background.

society was egalitarian (no inherited leadership or centralized authority), decision making in emergencies was local and efficient at the village level and especially at the household level. Despite careful dating and archaeological study, no changes in artifacts, architecture, settlement pattern, or other aspects of culture could be detected that might have been caused or affected by volcanic eruptions. The egalitarian Arenal societies were exceptionally resilient to these sudden massive stresses, especially when compared to hierarchically organized societies in other areas of Central America.

To the southeast of Arenal, just across the border in Panama, were the Barriles chiefdoms that lined both sides of the Rio Chiriqui (Linares and Ranere, 1980). These groups were competitive and engaged in frequent warfare, so it was advantageous for each to have a large population and to occupy and defend all arable land. When Volcan Baru erupted and spread a relatively minor deposit of volcanic ash (Figure 4), the modest decline in life support capacity of the environment was more than the local groups could withstand, and people had to migrate over the divide to the hot and humid Caribbean coast. The environment there was significantly different, forcing them to change their cultigens, their settlement pattern, and their culture, and they never returned to their homeland. They exemplify a society with dense populations living close to the threshold of sustainability; under such conditions, even a relatively minor perturbation was beyond their resilience and required drastic adjustments.

Numerous volcanic eruptions affected other ancient Mesoamerican societies. In many cases, the long-lasting effects were relatively minor. In spite of devastation during the eruptive impact and depopulation of the most severely affected area, people often reoccupied previously inhabited locations and did not exhibit significant societal changes after weathering formed new soils, and flora and fauna recovered near their pre-eruption state. An example is the ca. AD 660 Loma Caldera eruption in El Salvador that buried the Cerén site under 5–6 m of volcanic ash, resulting in the extraordinary preservation of houses, food, plants growing in gardens and agricultural fields, and the landscape (Sheets, 2002). The Cerén residents had to flee, and they never returned, but the eruption affected only a few square kilometers, so that most settlements in the valley were unaffected. The eruption produced no detectable culture change in the overall society through time.

Even the significantly larger eruption of Boqueron (Volcan San Salvador) in the tenth century AD left no long-standing scars on local societies. It caused major adaptive difficulties for an area estimated at 300 km^2 (Sheets, 2001), necessitating abandonment and relocation of refugees for at least a few decades until environmental recovery occurred. The society beyond the devastated area was unaffected and was the source of re-occupants along with the returning refugees, and cultural changes were negligible.

Summary

Volcanoes have posed hazards and opportunities to people for millennia. Volcanic products such as obsidian and basalt-andesite-dacite can be shaped into useful cutting, scraping, and grinding tools as well as construction stone. Volcanoes provide pigments including hematite, limonite, and cinnabar (mercuric sulfide), and volcanic ash weathers into clay that is useful for making pottery and earthen architecture. Volcanic soils have well-deserved reputations for fertility. People living near volcanoes can be affected by earthquakes that occur in association with eruptions, and lava flows can obliterate formerly arable soils, requiring centuries or millennia of weathering to recover fully. Ashfalls weather much more rapidly than

lavas, but many years or decades may be necessary before cultivation can be reestablished.

Societies vary in their vulnerability to volcanic stresses. Generally, the more egalitarian societies that have lower population densities and localized nodes of decision making react more rapidly and effectively. In contrast, hierarchically organized societies possessing high population densities and living close to the carrying capacity of their environments recover far more slowly if at all.

The complex and dynamic linkages between human agency and volcanic phenomena have formed important chapters in the history of our ancestors on this planet, and the significance of those relationships will continue into the foreseeable future.

Bibliography

Berry, J., 2007. *The Complete Pompeii*. New York: Thames and Hudson.

Castleden, R., 1990. *Minoans: Life in Bronze Age Crete*. London: Routledge.

Doumas, C., 1983. *Thera, Pompeii of the Ancient Aegean: Excavations at Akrotiri, 1967–79*. London: Thames and Hudson.

Dull, R. A., Southon, J. R., and Sheets, P., 2001. Volcanism, ecology, and culture: a reassessment of the Volcán Ilopango TBJ eruption in the southern Maya realm. *Latin American Antiquity*, **12**(1), 25–44.

Dull, R., Southon, J., Kutterolf, S., Freundt, A., Wahl, D., and Sheets, P., 2010. *Did the Ilopango TBJ Eruption Cause the AD 536 Event?* American Geophysical Union Conference, San Francisco, December 13–17, AGU Fall Meeting Abstracts 13: p. 2370. http://www.fundar.org.sv/referencias/dull_et_al_2010_AGU.pdf

Evans, S. T., and Webster, D. L., 2001. *Archaeology of Ancient Mexico and Central America: An Encyclopedia*. New York: Garland.

Friedrich, W. L., Kromer, B., Friedrich, M., Heinemeier, J., Pfeiffer, T., and Talamo, S., 2006. Santorini eruption radiocarbon dated to 1627–1600 B.C. *Science*, **312**(5773), 548.

Houston, M. S., 2000. Chinese climate, history, and state stability in AD 536. In Gunn, J. D. (ed.), *The Years Without Summer: Tracing A.D. 536 and Its Aftermath*. Oxford: Archaeopress. British Archaeological Reports, International Series, Vol. 872, pp. 71–78.

Larsen, L. B., Vinther, B. M., Briffa, K. R., Melvin, T. M., Clausen, H. B., Jones, P. D., Siggaard-Andersen, M.-L., Hammer, C. U., Eronen, M., Grudd, H., Gunnarson, B. E., Hantemirof, R. M., Naurzbaev, M. M., and Nicolussi, K., 2008. New ice core evidence for a volcanic cause of the A.D. 536 dust veil. *Geophysical Research Letters*, **35**, L04708, doi:10.1029/2007GL032450.

Leakey, M., 1979. 3–6 million years old: footprints in the ashes of time. *National Geographic*, **155**(4), 446–457.

Linares, O. F., and Ranere, A. J. (eds.), 1980. *Adaptive Radiations in Prehistoric Panama*. Cambridge, MA: Peabody Museum of Archaeology and Ethnology, Harvard University.

Manning, S. W., 2014. *A Test of Time and a Test of Time Revisited: The Volcano of Thera and the Chronology and History of the Aegean and East Mediterranean in the Mid-Second Millennium BC*. Oxford: Oxbow Books.

Oppenheimer, C., 2011. *Eruptions that Shook the World*. Cambridge: Cambridge University Press.

Plunket, P., and Uruñuela, G., 1998. Preclassic household patterns preserved under volcanic ash at Tetimpa, Puebla, Mexico. *Latin American Antiquity*, **9**(4), 287–309.

Renfrew, C., and Bahn, P. G., 2004. *Archaeology: Theories, Methods and Practice*, 4th edn. London: Thames and Hudson.

Robichaux, H. R., 2000. The Maya Hiatus and the AD 536 atmospheric event. In Gunn, J. D. (ed.), *The Years Without Summer: Tracing A.D. 536 and Its Aftermath*. Oxford: Archaeopress. British Archaeological Reports, International Series, Vol. 872, pp. 45–53.

Sheets, P., 2001. The effects of explosive volcanism on simple to complex societies in ancient Middle America. In Markgraf, V. (ed.), *Interhemispheric Climate Linkages*. San Diego: Academic, pp. 73–86.

Sheets, P. D. (ed.), 2002. *Before the Volcano Erupted: The Ancient Cerén Village in Central America*. Austin: University of Texas Press.

Siebe, C., 2000. Age and archaeological implications of Xitle volcano, southwestern Basin of Mexico-City. *Journal of Volcanology and Geothermal Research*, **104**(1–4), 45–64.

Siebe, C., Abrams, M., Macías, J. L., and Obenholzer, J., 1996. Repeated volcanic disasters in Prehispanic time at Popocatépetl, central Mexico: past key to the future? *Geology*, **24**(5), 399–402.

Smithsonian Institution, Global Volcanism Program http://www.volcano.si.edu/index.cfm

Cross-references

Cerén
Mass Movement
Olduvai
Pompeii and Herculaneum
Radiocarbon Dating
Santorini
Tephrochronology
Tsunamis

W

WELLS AND RESERVOIRS

Vernon L. Scarborough[1] and Kenneth B. Tankersley[2]
[1]Department of Anthropology, University of Cincinnati, Cincinnati, OH, USA
[2]Department of Anthropology and Department of Geology, University of Cincinnati, Cincinnati, OH, USA

Definition and context

Water management and engineered landscapes of past civilizations have recently drawn the attention of scholars in book-length examinations (Doolittle, 1990; Crouch, 1993; Scarborough and Isaac, 1993; Ronan and Needham, 1995; Doolittle, 2000; Denevan, 2001; Scarborough, 2003; Wilkinson, 2003; Lucero, 2006; Lucero and Fash, 2006; Ortloff, 2009; Scarborough, in press). The pressing influence of global climate warming today has raised concerns about water extraction and allocation, and the role of archaeology in identifying ancient systems of water use has the potential to inform the management of this most critical of all natural resources – more primary even than food. Past water systems were frequently clever and enduring constructions lasting sometimes for centuries; groups accretionally modified what came before, working within their environmental limitations and emphasizing conservation measures because of the lack of complex technologies and heavy dependencies on physical labor. Implicit in the deep time continuity of these systems is the notion of sustainability. Research into former methods and techniques of moving water to locales advantageous for humans (canalization) as well as extracting it by harvesting shallow water tables (wells) and/or storing it in open-surface reservoirs fills a sizable literature. The focus of this entry is water storage – inclusive of wells – as canalization is treated elsewhere in this volume.

Geoarchaeology of ancient wells and reservoirs

Wells and reservoirs are environmental magnets that accumulate sediments and the carbonate remains of invertebrates (e.g., ostracods and gastropods), carbonized and uncarbonized plant remains, pollen, and phytoliths from their catchment areas. Unless they have been dredged, they can be investigated like natural bodies of water using the same geoarchaeological techniques that integrate geochemistry, geochronology, mineralogy, and sedimentology. Because ancient reservoirs are frequently drained or seasonally depleted, organic indicators of past functions, especially pollen, phytoliths, and macrobotanical remains, can become highly degraded. To understand the complexities of ancient well and reservoir sediments, it is essential first to develop a detailed chronostratigraphy or dated depositional record. Strata and intervals within strata may document the timing of environmental and cultural transitions by preserving the biogeochemical and sedimentological record of the main sedimentary units. This analytical approach reveals the geological processes that create the sediments of wells and reservoirs – that is, the geologic record of the production, transport, and deposition of physical and chemical sediments – and ultimately the rates of environmental and cultural change.

Ideally, well and reservoir chronostratigraphy should be developed using both optically stimulated luminescence (OSL) and accelerator mass spectrometry (AMS) radiocarbon dating, though uncertainties are inherent in both dating methods. Radiocarbon samples can be contaminated with older carbon during transport and deposition or by young carbon from sources such as modern roots or burrowing organisms, and in the radiocarbon calibration curve, uncertainty increases with age. With OSL dating, there are uncertainties in the burial history of the sample, the background dose rate, the sample saturation history, and whether the sample was sufficiently exposed to light to reset the OSL signal. Yet despite these

A.S. Gilbert (ed.), *Encyclopedia of Geoarchaeology*, DOI 10.1007/978-1-4020-4409-0,

uncertainties, both methods are effective and powerful dating tools that substantially complement one another when used collectively.

Texture is the most important asset controlling the physical, chemical, and hydrological properties of well and reservoir sediments. Classification of their physical characteristics is accomplished using particle size or textural analysis. Particle size distribution (PSD) is determined by separating the gravel, sand, silt, and clay fractions with grading sieves using either a wet or dry method, by sedimentation, by pipette method, or using the faster but less accurate Bouyoucos hydrometer method. PSD is a fundamental geoarchaeological tool and an effective way to assess well and reservoir responses to anthropogenic and environmental conditions such as droughts, water retention, sediment transport, landscape stability, and soil erosion rates (Scarborough et al., 1999, 2010).

Powder X-ray diffraction (XRD) analysis can be used to reconstruct past environments and perhaps climate. Climate-sensitive clay minerals commonly occur in well and reservoir sediments, and their relative amounts correlate with climate episodes (Tankersley and Balantyne, 2010). XRD peak intensity ratios of minerals in well and reservoir sediment layers are diagnostic for different clay source areas and hydrometeorological transport processes in catchment areas. Thus, quantification of clay minerals in sediments by XRD may be used as a paleoenvironmental proxy. Clay-mineral-based climate fluctuations are correlative with marine oxygen-isotope records and provide a relatively simple and cost-effective tool for gaining insight into paleoclimate. Environmental sequences and climosequences of clay minerals in well and reservoir sediments are directly related to the availability and flux of water through the soil, which is a prime factor in weathering intensity. Clay minerals weather differently under climate conditions that vary in average annual rainfall. The amount of surface vegetation and microbial activity in depositional environments also bears a significant but indirect influence on the weathering of clay minerals.

At Tikal, Guatemala, XRD diffraction and petrographic analyses of reservoir sediments identified significant quantities of decomposed volcanic ash in the form of volcanogenic smectite and euhedral bipyramidal quartz crystals (Tankersley et al., 2011). X-ray fluorescence spectrometry (XRF) trace element content analysis using Zr/Y and Ni/Cr ratios of reservoir sediments from Tikal indicates an ash source from Central America (e.g., Guatemalan and Salvadoran). AMS radiocarbon dating of the smectite and crystalline quartz-rich reservoir sediments shows that volcanic ash fell during the Preclassic, Classic, and Postclassic Maya cultural periods (600 BC–AD 1500).

The magnetic properties of clays deposited in wells and reservoirs vary with changes in climate and human activity and can be measured using magnetic susceptibility (SI). Magnetic susceptibility values of core samples and excavation profiles can be obtained digitally using a time-dependent method that results in precise and repeatable data acquisition. Oscillating periods of warm and moist followed by cold and dry environments are potentially identifiable when SI measurements are taken from well and reservoir sediments at controlled depths below the surface. Warm and moist climatic conditions are associated with high SI values in well and reservoir clays, while cold and dry climatic conditions are associated with low SI values. There is also a statistically significant association of SI values and the relative percent composition of illite in well and reservoir clays. The percent composition of illite by depth is directly proportional to the SI values of reservoir clays. The latter pattern is likely the result of nanoparticles of magnetite attached to illite, with animal-sediment interaction partly responsible for the Fe-illite mineral relationship (Tankersley and Balantyne, 2010).

Stable carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) isotope values associated with insoluble soil organic matter (SOM) from well and reservoir sediments reflect vegetation in the catchment areas with differing photosynthetic pathways, such as C3 trees, shrubs, and herbs versus C4 grasses or CAM cacti and succulents. These carbon isotopes can also be used to distinguish open country versus dense canopy forest. Oxygen ($\delta^{18}O$) isotope values for ostracod and gastropod shells extracted from well and reservoir sediments can be used to evaluate water temperature, relative humidity, and seasonality. Nitrogen isotopes ($\delta^{15}N$) are affected by abiotic factors such as temperature and relative humidity. As a result, sediments in hotter, drier localities have higher $\delta^{15}N$ values than sediments in cooler, moister ones. Ancient polluting algal blooms may also be revealed by conducting $\delta^{15}N$ tests. Combined, these isotopes can be used to tease apart environmental changes, including major transitions in vegetation cover (e.g., shift from C4 to C3 dominance), as well as more subtle changes such as decreasing or increasing forest cover, grasslands, or desertification.

Like stable isotopes, terpenoid biomarkers can be used to constrain and reconstruct floral changes between major phylogenetic plant groups, thereby providing insight into how vegetation within the well and reservoir catchment area changed. Plant terpenoids are prenol lipids that represent one of the largest and most diverse groups of vascular plant compounds. Terpenoids have long been used as biomarkers, or chemical fossils, for higher plants in geologic sediments and oils, and they are diagnostic for plant taxonomy (Diefendorf, 2010). Variations in the abundances of these compounds may be used to constrain the plant groups from which organic matter was derived, and they have been invoked in reconstructions of paleoecology and paleoenvironments from well and reservoir sediments. Production of terpenoids by different plant species – including angiosperms and gymnosperms, and short and long leaf life-spans – has been characterized so that they now provide a basis to interpret abundance patterns in sediments. Terpenoids offer a unique opportunity to constrain floral composition changes in core samples when pollen or macrofloral analyses are not possible due to poor preservation or small sample size of the core or excavation samples.

Wells

The underground harvesting of the water table prior to hydraulic pumps was performed either by traditional hand-dug vertical shafts or by tapping natural groundwater exposures. Seeps and springs were frequently cleared of debris and opened for access via a shallow ponding area in close enough proximity for collecting and storing water, or managing it so as to provide an adequate head to accommodate water flow into a channel or canal. Examples include the thirteenth-century site areas of Glen Canyon (Sharrock et al., 1961) and Mesa Verde systems (Rohn, 1963) in the US Southwest, as well as the very early canalization effort noted from the ancient Olmec springs at Teopantecuanitlan of west Mexico ca. 1200 BC (Doolittle, 1990). Formal wells abound globally, but the earliest of these appear in Highland Mexico (Caran et al., 1996) and again in the US Southwest (Evans, 1951) by 10,000 years ago associated with the hunting and foraging peregrinations of the Paleoindians. In the Old World, the earliest known wells are likely those of Cyprus dating to a comparable period (Peltenburg et al., 2000). Their positioning likely influenced the seasonally structured movements of hunters and foragers in the former, while in the case of Cyprus and early Neolithic populations, more permanent occupation is implied.

Both springs and hand-dug wells have been an important source of water in nearly every society. With time and experimentation, unique adaptations have developed to harvest water more effectively within local environmental contexts. Simple technologies have evolved to accommodate the vertical lifting and containment of water when gravity cannot be used to relocate it. In the Old World, the advent of the *shaduf*, or well sweep, employed first in the Near East and widely used subsequently along the Nile, permitted the raising of water by way of a bucket and dipping line attached to a long pole positioned on a fixed fulcrum – but one allowed to rotate (Scarborough, 2003, p. 40). A heavy counterweight at the end of the pivoting pole, rope, and bucket was designed to drop the bucket into a low-lying well or body of water and then lift and relocate the contained water to a higher elevation. In the case of wells, bucket lifting obviously began with the tapping of shallow water tables manually by way of rope hoisting, though in ancient Mexico simple gallon jars were dipped into elevated groundwater via surficial wells that allowed the *pot irrigation* of individual plants in the immediate proximity (Flannery et al., 1967). In the Old World, horizontal bar and crank systems allowed the winding of rope immediately above a *puteal*, or well curb (Jansen, 1991; Crouch, 1993, p. 231). The subsequent use of the Archimedes screw, the water wheel or *noria*, and the significant role of the pulley further permitted the lifting of water's mass and fluid state, frequently with the aid of beasts of burden (Scarborough, 2003, p. 40).

Walk-in wells were accessed by foot and frequently associated with large subterranean reservoirs recharged by natural springs. One of the more elaborate examples was at thirteenth-century AD Casas Grandes in northern Mexico; identified by a 12 m vertical drop to the water table, it descended by a series of switchback stairs (DiPeso et al., 1974). In the highly karstic northern Yucatan, deep natural caves sometimes permitted ladder access to sizable pools of water. Near Bolonchan, a descent of 100 m below the surface allowed water collection via ceramic pots (Stephens, 1843, p. 96). In the Old World, karst topography allowed rock carved channels and pools as early as the Late Bronze Age (1500–1150 BC) at Mycenae, Tiryns, and Athens (Scarborough, 2003, pp. 146–152). The one at Athens was characterized by a depth below the Acropolis of 40 m and an entrance by means of eight flights of steps and several landings (Broneer, 1939). In Jerusalem, karstic jointing was altered to produce access to the springs of Gihon by 700 BC (Gill, 1991). Perhaps the most elaborate walk-in wells are the celebrated step wells of Gujarat and adjacent portions of western India and Pakistan. They display extremely elaborate architectural detail and were accessed by ornate steps; they were constructed as early as the third century AD with enduring use and alterations into the Mogul period (Livingston, 2002).

The highly sophisticated and labor-intensive *qanat*, *karez*, or *foggara* constructions represent the most expansive and clever of all well-driven systems. Probably originating in ancient Iran – though recent discoveries may indicate an Arabian Peninsula initiation – qanats are extensive "horizontal well systems," frequently running underground for kilometers (Lightfoot, in press). Gravity flow relocates the source to low-lying villages and towns away from the rugged and surficially waterless zone of extraction. Still active in present-day Iran, these systems entail a highly skilled set of craftsmen – guild-like – that excavate vertical shafts to access an aquifer usually below the colluvial/alluvial margins at the foot of a mountainous outcrop where water may accumulate. Once a "mother well" taps water at depths of 20–100 m – though the well shaft at Gonabad, Iran, near the Afghan border drops 300 vertical meters (English, 1966) – lateral tunneling commences (Figure 1). Careful and highly controlled digging entails a gradient of about 1:1,500 so as to prevent either channel course erosion or significant sedimentation. Today, sizable prefabricated, oval-shaped conduit segments of concrete are carried into the tunnel excavations to shore up pockets of sand encountered as the digging proceeds. In Yazd, Iran, attempts are being made to preserve the tradition of *qanat* or *karez* building in a location with a long history of tunnel use; here, horizontal shafts can cross yet deeper tunnels in a complex network of buried waterways (Lightfoot, in press). From the air, *qanat* systems appear as a series of "chain wells" revealing donut-like mounds and the locations of their underground pathways (Figure 2). These "skylights" permit the removal of detritus and excavated waste and remain crucial for maintenance. In the New World, shallow versions of the *qanat* system, *puquios*, are indicated

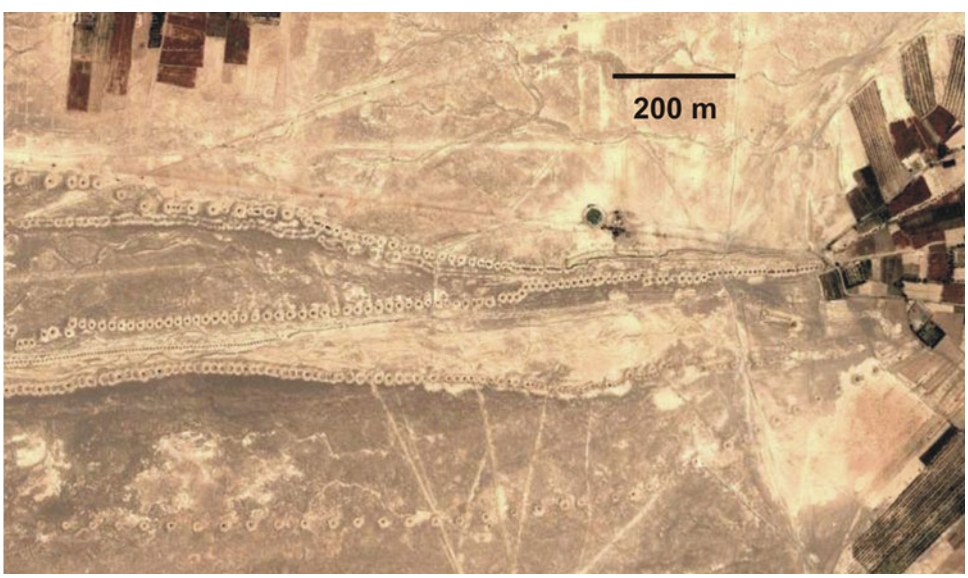
Wells and Reservoirs, Figure 1 Inside a qanat near Quetta, Baluchistan, Pakistan (Courtesy of V. Scarborough).

to have been pre-Hispanic in Peru and northern Chile (Schreiber and Lancho Rojas, 1995; Schreiber and Lancho Rojas, in press), though controversy remains over the prospect that they were introduced by the Spanish (cf. Woodbury and Neely, 1972; Barnes and Fleming, 1991 in Mexico).

Although not designed to extract water for potable uses, the sunken gardens of ancient Peru were excavated to a frequently dropping water table. Near the great Chimu center of Chan Chan, field depression descended 5–7 m before the fields were abandoned (Moseley, 1983; Moseley, in press). On certain Pacific island atolls, pit cultivation, or a less expansive version of the Peruvian adaptation, was practiced (Kirch, 1994, p. 5). And in some dolinen (sinkholes or *rejollada*) identified with elevated water-table soils of northern Yucatan, the ancient Maya grew cacao and perhaps other environmentally temperamental plants (Gómez-Pompa et al., 1990).

Reservoirs and dams

Reservoirs are open catchment basins that hold intermittent surface runoff or water from formal canals or less formal channels. *Storage dams* are frequently associated with reservoirs; *diversion dams* (or *weirs*) are employed by canal users. Dams built at the egresses of reservoirs can slow the velocity of water coursing through them, especially during flash flooding. At other times, they can serve to raise reservoir water levels by slowing outflow into issuing canals. Generally, reservoirs and storage dams are constructed in regions without dependable riverine



Wells and Reservoirs, Figure 2 Satellite view of a section of the qanat system near Abarkuh, Yazd Province, Iran (Imagery © 2012 CNES/Spot Image, Digital Globe, GeoEye, Map data © 2012 Google).

water sources. These features have an ancient past, and many small, deliberately constructed ponding areas have probably gone unnoticed as a consequence of rapid sedimentation following their disuse (Scarborough, 2003, p. 47).

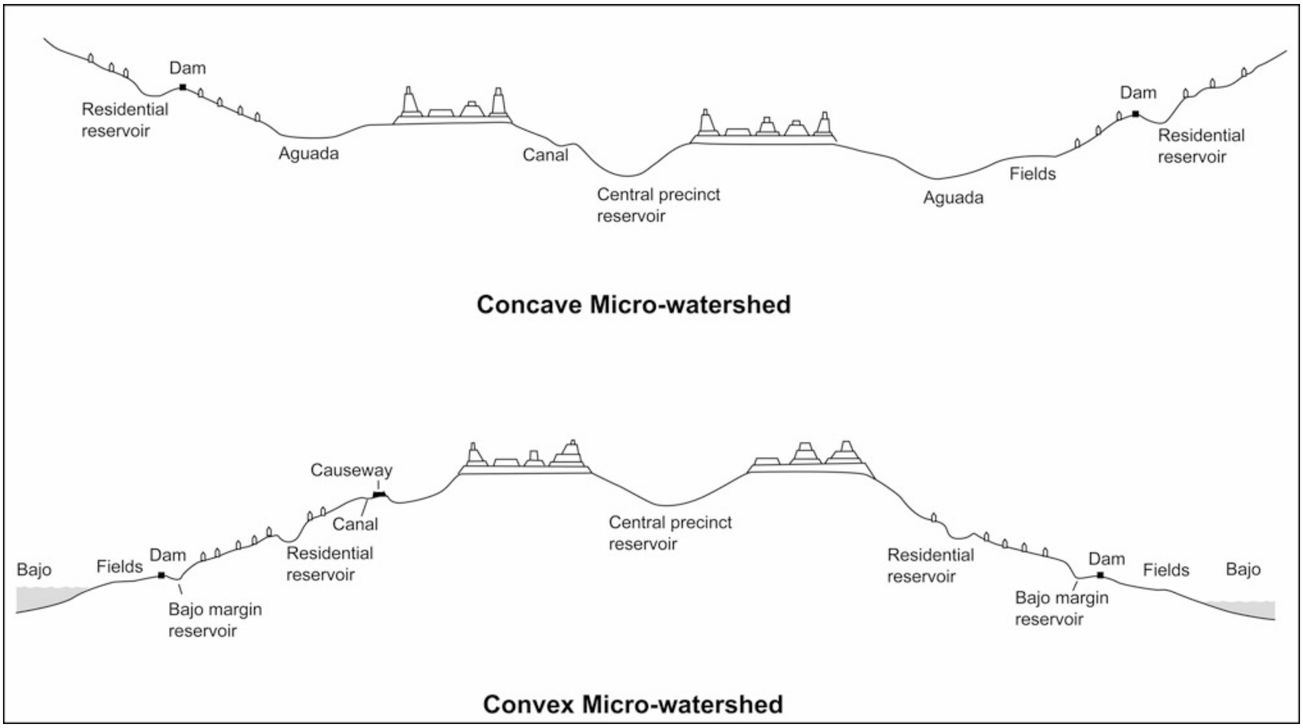
New World

William Doolittle (1990) provides the best overview of early water management systems from ancient Mexico. He notes again the small Olmec site of Teopantecuanitlan and the first appearance of a *gravity dam*, one that contains the perpendicular flow of water due to its mass and not its shape, for water storage in Mesoamerica. The most massive pre-Hispanic dam construction in the New World also occurs in Mexico within the Tehuacan Valley (Woodbury and Neely, 1972; Aiuvalasit et al., 2009). The Perrón Dam has an initiation date of 700 BC, but as early as the Late Formative (400 BC–AD 100), a gravity dam of 100 × 400 × 18 m was constructed. The reservoir was provided with a substantial *cofferdam*, the partitioning of a reservoir system to collect head-end sediment in a *silting tank* before the water entered a greater holding basin and/or to accommodate water storage when the principal reservoir necessitated dredging near the ingress to the sizable main tank. The first reported *arch dam* in the New World appears in ancient Oaxaca, Mexico, near the large center of Monte Albán (O'Brien et al., 1982). This Xoxocotlán Piedmont dam was 10 m high and 80 m long, and it was built between 550 and 150 BC with a V-shaped plan pointing upstream, thereby providing a design as dependent on structural orientation as on mass. At the low-density urban population aggregate of Tikal, Guatemala, a gravity dam of comparable size to that at Xoxocotlán was associated with posited sluices of diminutive size and a nearby cofferdam (Scarborough et al., 2012). Perhaps the greatest investment in dam construction is found during the Aztec period of the Valley of Mexico (AD 1350–1519) in which the freshwater infused embayment surrounding the island city of Tenochtitlan was separated from the adjacent saline Lake Texcoco by the massive Netzahualcoyotl Dike, with the widespread incorporation of *chinampas* – raised field plots (Sanders et al., 1979).

In the arid US Southwest and northern Mexico, reservoirs occur in several contexts. The ancient community of Casas Grandes (Chihuahua, Mexico) again reveals a complex reservoir system with both water retention basins and stone-lined silting tanks (DiPeso et al., 1974). The ancient Hohokam of south central Arizona frequently located their largest reservoirs away from their elaborate canalization schemes but dealt efficiently with evaporative loss by increasing volume via depth while holding surface area constant (Scarborough, 1988; Bayman and Fish, 1992; Fish and Fish, in press). At water-scarce Chaco Canyon, the several pueblos dating to AD 1020–1120 used diversion dams to redirect seasonal runoff into *overflow reservoirs*, small depressions employed to slow the water's erosive effects as well as provide subsequent agricultural use of the ponded resource (Vivian, 1974).

The cisterns of both the Old and New Worlds looked and functioned in a similar manner. Those associated with the ancient Greek atrium fed by an *impluvium*, a shallow and flat-bottomed basin (Crouch, 1993), and the sizable Nabataean cisterns of Petra (Ortloff, 2005) and the extremely dry Negev Desert (Evenari et al., 1971) were functionally mimicked in northern Yucatan. In the Puuc Hills of the ancient Maya Lowlands, large subterranean bell-shaped cisterns, or *chultuns*, used concretized dish-shaped catchments to drain water off elevated housemounds into constricted bottleneck openings at the household level (McAnany, 1990). Elsewhere in the Maya Lowlands, quarry scars resulting from building operations in towns and "cities" were frequently converted to open-surface reservoirs (Scarborough, 1993, 1994). At the Late Preclassic community of Cerros in northern Belize (ca. 200 BC–AD 150), a canal-like feature circumscribing the margins of the site formed a social boundary but also functioned as an elongated moat-like tank receiving runoff from several zones during the rainy season. By using *sills* – horizontally laid stones positioned to extend the reach to ponded water as its level descended during the dry season – access was allowed and collection was enabled in basal depressions or *basin canals* (Scarborough, 1983, 1991). The large site of Edzna, in Campeche, Mexico, also dating to the Late Preclassic, incorporated a system of wide linear canals to drain and harvest water (Matheny, 1976), though some controversy exists over the degree to which these basins may have been large-scale *grikes*, or fissures, eroded naturally along cracks and joints in the limestone (Butzer, 1996). In any case, these Late Preclassic water systems and landscapes were frequently constructed in low-lying settings – called *concave microwatersheds* (Figure 3 upper) – and depended on natural runoff from the adjacent high ground for seasonal recharge. *Aguadas*, or ponds that were frequently human modified from eroding sinkholes, are ubiquitous in the Maya Lowlands and were used widely by rural populations. Also, the *bajos*, huge internally draining, natural depressions of karst origin (*polje*), in this same region are hypothesized by some to have been partially altered to hold water in shallow canals flanking drained or slightly raised fields (Harrison, 1977; cf. Scarborough, 2006; Scarborough, 2007).

During the Classic Period (AD 250–800), several urban settings modeled their water management after a *convex microwatershed* adaptation (Figure 3 lower). Sizable communities located on ridges or hillocks used plastered public architectural surfaces to direct seasonal precipitation into elevated tank systems for subsequent dry season gravity flow release (Scarborough, 1993; Scarborough, 1994; Scarborough and Burnside, 2010). Unlike the earlier Late Preclassic period, these later systems were highly managed and much less passive in terms of catchment controls. One of the grand water management designs



Wells and Reservoirs, Figure 3 (*Upper*) Concave microwatershed in the Maya Lowlands. (*Lower*) Concave microwatershed in the Maya Lowlands.

within an urban context was at Tikal, Guatemala (Scarborough and Gallopin, 1991; Scarborough et al., 2012), where the nested summit was identified by a triangular set of causeways (also serving as dams) enclosing ca. 62 ha of central precinct space, with much of the bedrock sculpted and quarried to erect the adjacent towering pyramids and massive acropolises. With annual rainfall of 1,500 mm, over 900,000 m^3 of precipitation would fall on the central precinct area and easily fill the several elevated reservoirs seasonally to their maximum volume of 250,000 m^3. Through a series of descending dams and tanks, water was gravity released to a surrounding population during the dry season, a community otherwise distant from a year-round surface water source, either lake or stream. Evidence indicates that sand filters were placed at the ingress of tanks to aid in curbing contaminants from the highly trafficked water catchments within the urban core (Tankersley et al., 2011; Scarborough et al., 2012).

Although the semiarid Andean Highlands as well as coastal Ecuador and Peru demonstrate several water management advances (see entry "Canals and Aqueducts in the Ancient World" by Ortloff, this volume), ancient populations were less dependent on reservoirs because of their sophisticated canalization investment in moving water year around. Of special interest, however, was the "geologic water storage" described by Fairley (2003) in which porous sands were introduced into a dammed depression allowing the saturation of the introduced soil while curbing the open-surface evaporation of the water it contained. This human-made aquifer was tapped by way of a specially designed wall that acted as a seep or spring source. In addition to the great modifications made to the margins of Lake Titicaca that permitted the trapping of water for raised field agriculture (Kolata, 1991; Erickson, 1993), the Amazonian lowland systems show a wide variety of landscaping alterations that optimally contained water as well as mechanisms to disperse it based on the highly seasonal swelling of streams and rivers (Denevan, 2001; Erickson, 2006; Erickson, in press). Ring ditch systems clearly defined community boundaries, but also provided a ready fish source as well as other usable animal and plant foods (Walker, 2008).

Old World

The earliest reservoir systems appear in the Near East precociously at the late fourth millennium town of Jawa, Jordan (Helms, 1981). Within an extremely arid setting (150 mm annual rainfall), this highly engineered community maintained ten reservoirs behind gravity dams constructed with downstream *revetments* (stone buttresses), spillways, and sluice gates. Positioned within a small, highly constricted valley, Jawa received 2,000,000 m^3 of water annually, frequently in the form of storm surges. Nevertheless, with the estimated 15,000 tons of basalt devoted to the construction of the hydraulic system alone, perhaps 70,000 m^3 of water was

Wells and Reservoirs, Figure 4 Pastoralist and gathering herd using "oasis" setting at El Fasher, Darfur, Sudan; a living example of "hafir" function (Courtesy V. Scarborough).

contained to sustain a population of about 5,600. In one case, a *waterface apron* of stone extended into the lower reaches of the tank designed for seepage control as well as retarding the effects of wave action. Functioning as a causeway (as noted in the New World examples), the dam was 4–5 m high and 80 m long. Other early dams include Helwan (south of Cairo) which is estimated to have required 60,000 tons of gravel and 40 tons of stone masonry around 2700 BC (Helms, 1981; Hassan, in press).

In the Sahel of northern Sudan, East Africa, sizable reservoirs located far from the Nile and without formal channels leading in or out are called *hafirs* (Crowfoot and Griffith, 1911). Located in proximity to Meroitic communities (350 BC–AD 350), these rain-fed tanks may have been as important to the townsfolk as to a foraging pastoral population moving from tank to tank (Figure 4). In this socioeconomic equation, both groups would benefit from the water source, with the townspeople obtaining the added advantage of milk, wool, and meat (Scarborough, 2003, pp. 57, 82–83). At a comparable period, the Marib Dam of Yemen was constructed to provide a canalized source of water for drinking and irrigation. Although the Marib Dam was the largest such installation (with final expanded dimensions of 14 m in height by 600 m in length), and it was in place by the sixth century BC, 80 smaller dams ranging in scale from 1 to 5 m high by 100–200 m long were built in the surrounding region (Bowen and Albright, 1958; Garbrecht, 1987; Wilkinson, 2003). The North African Maghrib was colonized by early Rome, resulting in the damming of sizable segments of several *wadis*, which are *arroyos* or gullies. The largest of these dams was across the Wadi Caam; it extended over 900 m and was built with a poured concrete core and cut-stone veneer (Shaw, 1984, p. 152). Nevertheless, the hydraulic engineering imposed by the Romans was more effective in the European mainland than it was when applied to North Africa and the Near East because the degree of aridity and kind of topographic relief could result in infrequent but highly damaging runoff surge events. Such events were less controllable with the introduced fixed-dam technology (Kennedy, 1995). The earliest well-reported dam in Europe appears in the Late Bronze Age (1500–1150 BC) within the Argolid, Greece. The Tiryns Dam was a diversion feature, but the dam type continues in use and was little modified by the Romans (Zangger, 1994).

Egyptian Nilotic waters and their annual sediment load were deposited in large basins along the Nile floodplain. These basins acted as reservoirs and silt traps; water was conducted through a series of short canals and embankments into shallow tanks until the silt level was sufficiently high that they could be converted to planting surfaces during pharaonic periods (Hamdan, 1961; Butzer, 1976). A similar condition was also reported along the Euphrates during Old Babylonian times (Hedrick, 1997). Generally, little evidence for centralized hydraulic control by early states exists for this or any other ancient civilization yet noted (Butzer, 1976; Scarborough, 2003). Nevertheless, during the Middle Kingdom (2040 BC) and subsequent intervals of aridity, lake levels in the Faiyum Depression were manipulated by a series of dams and dikes as a consequence of state sponsorship (Hassan, in press).

The largest preindustrial period reservoirs appear in South Asia. The earliest investments in tank construction from this part of the world come from Harappan Pakistan and western India between 2500 and 1900 BC (Possehl, 1997; Scarborough, 2003; Possehl, in press), with the rectangular basin – 219 × 37 m, and walls to a depth of 4.5 m – identified at the Gujarat port community of Lothal (Allchin and Allchin, 1982; Possehl, 1997). The great city of Mohenjo-daro in Sindh Province was defined by a central acropolis containing a rectilinear Great Bath with dimensions of 12 × 7 × 3 m. This structure was built of fired brick, sealed with bitumen, accessed by formalized inset stairs, and drained by a high corbel-vaulted passage at the Citadel's margins. This well-known "bath," identified with a highly sanitized emphasis on purity manifest primarily by waterworks (including sump pits and indoor toilets) at Harappan cities, reflects a degree of ritualized water control unlike any noted for other early civilizations (Possehl, in press).

Much larger reservoir systems were especially elaborated in Sri Lanka's dry zone as early as the first century AD and frequently constructed by damming major rivers and streams. Ancient texts distinguish between large tanks, village tanks, and feeder tanks (Gunawardana, 1971). By the fifth century, the length and height of dams could be enormous; the Kala Wewa tank at the city of Anuradhapura was 27 m high and over 14 km long, resulting in a reservoir 65 km in circumference that fed a canal system extending over 90 km from the reservoir source (Leach, 1959). The comparably huge reservoir called the Parakrama Samudra (Sea of Parakrama I, after the king responsible for its expansion) provided piped water to the royal baths at the subsequent capital of Polonnaruwa. Because of the pressure exerted on the sidewalls of these dams, the sluices releasing those waters were ingeniously adapted. The *bisokotuva*, or cistern sluice, was designed to channel tank waters by routing their release underneath the dam via a series of interlocking vertically nested cylinders – today, bottomless pots – within the deepest reaches of the tank, stacked and descending to a shallow, tightly sealed, subterranean tunnel that issued at the downstream side of the dam (Gunawardana, 1978). With rising or dropping surface water levels within the reservoir, individual cylinder segments were added or removed to accommodate discharge demands. Large tanks of considerable complexity are also identified in Upper Burma (Pagan dynasties – Stargardt, 1983; Bray, 1986), eastern Java (Majahapit kingdom – Miksic, 1999), and among the sophisticated and ornate architectures of the Cambodian Khmer Empire (Groslier, 1979; Higham, 1989; Fletcher et al., in press).

Perhaps the largest city of preindustrial times was Angkor, Cambodia, now estimated to have enclosed an area of 1,000 km^2 (Evans et al., 2007; Fletcher et al., 2008) and supported a population of 600,000 (Higham, 1989). This hydraulic city was reestablished by King Indravarman by the late ninth century with hinterland irrigation extending over at least 167,000 ha (Groslier, 1979; Bray, 1986; Higham, 1989). The highly symmetrical, rectangular-shaped, east-to-west-oriented *baray* (enormous tanks) slowed and contained the movement of water through the city (Evans et al., 2007; Fletcher et al., 2008). The first sizable baray constructed by Indravarman covered 300 ha and had a capacity of 10,000,000 m^3 of water. However, his kingly successors were responsible for the Eastern and Western Barays that held 70,000,000 and 60,000,000 m^3, respectively. When coupled with the moat surrounding the gigantic temple-mausoleum of Angkor Wat and a Northern Baray, another 15,000,000 m^3 was made available. An additional 800 smaller tanks positioned along axial avenues throughout the city demonstrate the scale of water management. Ortloff (2009) has recently proposed that the water system was established and maintained to keep soils saturated and thereby prevent monumental constructions from sinking into the sandy base stratum on which the city rests. Furthermore, the wet seasonal recharge of the baray may well have allowed the predictable and controlled release of north to south, downslope filtering of water into low-lying rice paddies through the porous sands.

Ancient China invested in a highly sophisticated set of water management undertakings with the sponsorship of the state as indicated by several landscape and technological adaptations (Bray, 1986; Ronan and Needham, 1995; Gu et al., in press). Nevertheless, reservoirs tended to consist of small ponds adapted to rice cultivation, especially in the south and central portions of the country where rainfall was adequate and, unlike other regions of Asia, relatively predictable. Late Han grave offerings (AD 25–220) reveal clay models of these systems (Bray, 1986). The Peony Dam, however, constructed at ca. 600 BC, produced a reservoir enclosure with a circumference of nearly 100 km that was capable of the controlled flooding of 24,000 km^2 within a flat valley adjacent to the Yangtze River (Ronan and Needham, 1995).

Summary

Although many more ancient water storage and extraction examples could be drawn from the archaeological record – e.g., the later function of millponds (see Neely, 2011; Brykala and Podgorski, 2014) – those identified here provide a representative sample of the range of adaptations made by humans throughout our deep past. Given the limitations of technology, especially in the New World, these systems provide insights into their reapplication potential in portions of the world today where high-tech energy sources may be limited or lacking altogether. This presentation has focused on the functionality of wells, reservoirs, and their waters put to both potable and agricultural ends. However, the influence of political and ideological decision making by way of the adaptations actually manifest must also be assessed. For the purposes of this entry, functionality has been stressed only (for broader cultural implications, see Scarborough, 1998; Scarborough, 2003; Scarborough and Lucero, 2010).

Bibliography

Aiuvalasit, M. J., Neely, J. A., and Bateman, M. D., 2009. New radiometric dating of water management features at the prehistoric Purrón Dam Complex, Tehuacán Valley, Puebla, México. *Journal of Archaeological Science*, **37**(6), 1207–1213.

Allchin, B., and Allchin, R., 1982. *The Rise of Civilization in India and Pakistan*. Cambridge: Cambridge University Press.

Barnes, M., and Fleming, D., 1991. Filtration-gallery irrigation in the Spanish New World. *Latin American Antiquity*, **2**(1), 48–68.

Bayman, J. A., and Fish, S. K., 1992. Reservoirs and locational shifts in Sonoran Desert subsistence. In Croes, D. R., Hawkins, R. A., and Isaac, B. L. (eds.), *Long-Term Subsistence Change in Prehistoric North America*. Greenwich, CT: JAI Press. Research in Economic Anthropology, Supplement, Vol. 6, pp. 267–306.

Bowen, R. L., Jr., and Albright, F. P., 1958. *Archaeological Discoveries in South Arabia*. Baltimore: The Johns Hopkins University Press.

Bray, F., 1986. *The Rice Economies: Technology and Development in Asian Societies*. Oxford: Blackwell.

Broneer, O., 1939. A Mycenaean fountain on the Athenian Acropolis. *Hesperia*, **8**(4), 317–430.

Brykala, D, and Podgorski, Z., (2014). Watermills and mill ponds: the effects of human impact on rivers in Poland. In Scarborough, V. L. (ed.), *Water and Humanity: Historical Overview*. Paris: UNESCO Publishing.

Butzer, K. W., 1976. *Early Hydraulic Civilization in Egypt: A Study in Cultural Ecology*. Chicago: University of Chicago Press.

Butzer, K. W., 1996. Irrigation, raised fields and state management: Wittfogel redux? *Antiquity*, **70**(267), 200–204.

Caran, S. C., Neely, J. A., Winsborough, B. M., Ramirez Sorensen, F., and Valastro, S., Jr., 1996. A Late Paleo-Indian/Early Archaic water well in Mexico – possible oldest water-management feature in the New World. *Geoarchaeology*, **11**(1), 1–35.

Crouch, D. P., 1993. *Water Management in Ancient Greek Cities*. New York: Oxford University Press.

Crowfoot, J. W., and Griffith, F. L., 1911. *The Island of Meroë (Archaeological Survey of Egypt, Memoir 19)*. London: Egypt Exploration Fund.

Denevan, W. M., 2001. *Cultivated Landscapes of Native Amazonia and the Andes*. Oxford: Oxford University Press.

Diefendorf, A. F., 2010. *Environmental and Ecological Constraints on Molecular and Isotopic Signatures in Terrestrial Organic Carbon*. Ph.D. dissertation, Department of Geosciences, The Pennsylvania State University, University Park.

DiPeso, C. C., Rinaldo, J. B., and Fenner, G. J., 1974. *Casas Grandes: A Fallen Trading Center of the Gran Chichimeca, volume 4 (Architecture and Dating Methods) and 5 (Architecture)*. Flagstaff, AZ: Northland Press.

Doolittle, W. E., 1990. *Canal Irrigation in Prehistoric Mexico*. Austin: University of Texas Press.

Doolittle, W. E., 2000. *Cultivated Landscapes of Native North America*. Oxford: Oxford University Press.

English, P. W., 1966. *City and Village in Iran: Settlement and Economy in the Kirman Basin*. Madison: University of Wisconsin Press.

Erickson, C. L., 1993. The social organization of Prehispanic raised field agriculture in the Lake Titicaca Basin. In Scarborough, V. L., and Isaac, B. L. (eds.), *Economic Aspects of Water Management in the Prehispanic New World*. Greenwich, CT: JAI Press. Research in Economic Anthropology, Supplement, Vol. 7, pp. 369–426.

Erickson, C. L., 2006. The domesticated landscapes of the Bolivian Amazon. In Balée, W., and Erickson, C. L. (eds.), *Time and Complexity in Historical Ecology: Studies in the Neotropical Lowlands*. New York: Columbia University Press, pp. 235–278.

Erickson, C. L., (in press) Pre-Columbian water management in Lowland South America. In Scarborough, V. L. (ed.), *Water and Humanity: Historical Overview*. Paris: UNESCO Publishing.

Evans, G., 1951. Prehistoric wells in eastern New Mexico. *American Antiquity*, **17**(1), 1–9.

Evans, D., Pottier, C., Fletcher, R., Hensley, S., Tapley, I., Milne, A., and Barbetti, M., 2007. A comprehensive archaeological map of the world's largest preindustrial settlement complex at Angkor, Cambodia. *Proceedings of the National Academy of Science*, **104**(36), 14277–14282.

Evenari, M., Shanan, L., and Tadmor, N., 1971. *The Negev; The Challenge of a Desert*. Cambridge: Harvard University Press.

Fairley, J. P., Jr., 2003. Geological water storage in Pre-Columbian Peru. *Latin American Antiquity*, **14**(2), 193–206.

Fish, S., and Fish, P., (in press) Hohokam canal and water systems. In Scarborough, V. L. (ed.), *Water and Humanity: Historical Overview*. Paris: UNESCO Publishing.

Flannery, K. V., Kirkby, A. V., Kirkby, M. J., and Williams, A. W., Jr., 1967. Farming systems and political growth in ancient Oaxaca. *Science*, **158**(3800), 445–454.

Fletcher, R., Penny, D., Evans, D., Pottier, C., Barbetti, M., Kummu, M., and Lustig, T., 2008. The water management network of Angkor, Cambodia. *Antiquity*, **82**(317), 658–670.

Fletcher, R., Evans, D., Penny, D., Pottier, C., Kummu, M., and Lustig, T., (in press). In Scarborough, V. L. (ed.), *Water and Humanity: Historical Overview*. Paris: UNESCO Publishing.

Garbrecht, G., 1987. Irrigation throughout history: problems and solutions. In Wunderlich, W. O., and Prins, J. E. (eds.), *Water for the Future; Water Resources Developments for the Future. Proceedings of the International Symposium on Water for the Future, Rome, 6–11 April 1987*. Rotterdam/Boston: A.A. Balkema.

Gill, D., 1991. Subterranean waterworks of biblical Jerusalem: an adaptation of a karst system. *Science*, **254**(5037), 1467–1471.

Gómez-Pompa, A., Salvador Flores, J., and Aliphat Fernández, M., 1990. The sacred cacao groves of the Maya. *Latin American Antiquity*, **1**(3), 247–257.

Groslier, B. P., 1979. La cité hydraulique angkorienne: exploitation ou surexploitation du sol. *Bulletin de l'Ecole française d'Extrême-Orient*, **66**, 161–202.

Gu, H., Chen, M., and Wang, J., (in press). Irrigation civilization of ancient China (4000 BCE–1900 CE). In Scarborough, V. L. (ed.), *Water and Humanity: Historical Overview*. Paris: UNESCO Publishing.

Gunawardana, R. A. L. H., 1971. Irrigation and hydraulic society in early Medieval Ceylon. *Past and Present*, **53**, 3–27.

Gunawardana, R. A. L. H., 1978. Hydraulic engineering in ancient Sri Lanka: the cistern sluice. In Prematilleke, L., Indrapala, K., and van Lohuizen-de Leeuw, J. E. (eds.), *Senarat Paranavitana Commemoration Volume*. Leiden: E. J. Brill, pp. 61–74.

Hamdan, G., 1961. Evolution of irrigation agriculture in Egypt. In Stamp, L. D. (ed.), *A History of Land Use in Arid Regions*. Paris: UNESCO. Arid Zone Research, Vol. 17, pp. 119–142.

Harrison, P. D., 1977. The rise of the bajos and the fall of the Maya. In Hammond, N. (ed.), *Social Process in Maya Prehistory*. New York: Academic, pp. 469–508.

Hassan, F., (in press). Ancient Egypt and the Nile. In Scarborough, V. L. (ed.), *Water and Humanity: Historical Overview*. Paris: UNESCO Publishing.

Hedrick, R. M., Jr., 1997. *The Waters of Babylonia: The Management of Water Resources in the Old Babylonian Period*. PhD Dissertation. Cincinnati: Hebrew Union College.

Helms, S. W., 1981. *Jawa: Lost City of the Black Desert*. London: Methuen.

Higham, C., 1989. *The Archaeology of Mainland Southeast Asia*. Cambridge: Cambridge University Press.

Jansen, G. C. M., 1991. Voorzieningen van water, sanitair en afvalwaterafvoer in het Romeinse provinciestadje Herculaneum (Italie). *H2O: Tijdschrift voor Watervoorziening en Afvalwaterbehandeling*, **24**(7), 180–185.

Kennedy, D., 1995. Water supply and use in the southern Hauran, Jordan. *Journal of Field Archaeology*, **22**(3), 275–290.

Kirch, P. V., 1994. *The Wet and the Dry: Irrigation and Agricultural Intensification in Polynesia*. Chicago: University of Chicago Press.

Kolata, A. L., 1991. The technology and organization of agricultural production in the Tiwanaku State. *Latin American Antiquity*, **2**(2), 99–125.

Leach, E. R., 1959. Hydraulic society in Ceylon. *Past and Present*, **15**, 2–26.

Lightfoot, D., in press. Function, distribution, and history of Old World qanats. In Scarborough, V. L. (ed.), *Water and Humanity: Historical Overview*. Paris: UNESCO Publishing.

Livingston, M., 2002. *Steps to Water: The Ancient Stepwells of India*. New York: Princeton Architectural Press.

Lucero, L. J., 2006. *Water and Ritual: The Rise and Fall of Classic Maya Rulers*. Austin: University of Texas Press.

Lucero, L. J., and Fash, B. W. (eds.), 2006. *Precolumbian Water Management: Ideology, Ritual, and Power*. Tucson: University of Arizona Press.

Matheny, R. T., 1976. Maya Lowland hydraulic systems. *Science*, **193**(4254), 639–646.

McAnany, P. A., 1990. Water storage in the Puuc region of the northern Maya Lowlands: a key to population estimates and architectural variability. In Culbert, T. P., and Rice, D. (eds.), *Precolumbian Population History in the Maya Lowlands*. Albuquerque: University of New Mexico Press, pp. 263–284.

Miksic, J. N., 1999. Water, urbanization, and disease in ancient Indonesia. In Bacus, E. A., and Lucero, L. J. (eds.), *Complex Polities in the Ancient Tropical World*. Arlington: American Anthropological Association. Archeological Papers of the American Anthropological Association, Vol. 9, pp. 167–184.

Moseley, M. E., 1983. The good old days were better: agrarian collapse and tectonics. *American Anthropologist NS*, **85**(4), 773–799.

Moseley, M. E., (in press). The Central Andean Cordillera: adaptation to extreme aridity and altitude. In Scarborough, V. L. (ed.), *Water and Humanity: Historical Overview*. Paris: UNESCO Publishing.

Neely, J. A., 2011. Sasanian period drop-tower gristmills on the Deh Luran Plain, southwestern Iran. *Journal of Field Archaeology*, **36**(3), 232–254.

O'Brien, M. J., Mason, R. D., Lewarch, D. E., and Neely, J. A., 1982. *A Late Formative Irrigation Settlement below Monte Albán*. Austin: University of Texas Press.

Ortloff, C. R., 2005. The water supply and distribution system of the Nabataean city of Petra (Jordan), 300 BC–AD 300. *Cambridge Archaeological Journal*, **15**(1), 93–109.

Ortloff, C. R., 2009. *Water Engineering in the Ancient World*. Oxford: Oxford University Press.

Peltenburg, E., Colledge, S., Croft, P., Jackson, A., McCartney, C., and Murray, M. A., 2000. Agro-pastoralist colonization of Cyprus in the 10th millennium BP: initial assessments. *Antiquity*, **74**(286), 844–853.

Possehl, G. L., 1997. The transformation of the Indus Civilization. *Journal of World Prehistory*, **11**(4), 425–472.

Possehl, G. L., (in press). Water in South India and Sri Lanka: agriculture, irrigation, politics, and purity. In Scarborough, V. L. (ed.), *Water and Humanity: Historical Overview*. Paris: UNESCO Publishing.

Rohn, A. H., 1963. Prehistoric soil and water conservation on Chapin Mesa, southwestern Colorado. *American Antiquity*, **28**(4), 441–455.

Ronan, C. A., and Needham, J., 1995. *The Shorter Science and Civilization in China*. Cambridge: Cambridge University Press, Vol. 5.

Sanders, W. T., Parsons, J. R., and Santley, R. S., 1979. *The Basin of Mexico: Ecological Processes in the Evolution of a Civilization*. New York: Academic.

Scarborough, V. L., 1983. A Preclassic Maya water system. *American Antiquity*, **48**(4), 720–744.

Scarborough, V. L., 1988. A water storage adaptation in the American Southwest. *Journal of Anthropological Research*, **44**(1), 21–40.

Scarborough, V. L., 1991. *The Settlement System in a Late Preclassic Maya Community. Archaeology at Cerros, Belize, Central Americax*. Dallas: Southern Methodist University Press, Vol. 3.

Scarborough, V. L., 1993. Water management in the southern Maya Lowlands: an accretive model for the engineered landscape. In Scarborough, V. L., and Isaac, B. L. (eds.), *Economic Aspects of Water Management in the Prehispanic New World*. Greenwich, CT: JAI Press. Research in Economic Anthropology, Supplement, Vol. 7, pp. 17–69.

Scarborough, V. L., 1994. Maya water management. *Research and Exploration*, **10**(2), 184–199.

Scarborough, V. L., 1998. Ecology and ritual: water management and the Maya. *Latin American Antiquity*, **9**(2), 135–159.

Scarborough, V. L., 2003. *The Flow of Power: Ancient Water Systems and Landscapes*. Santa Fe: School of American Research Press.

Scarborough, V. L., 2006. An overview of Mesoamerican water systems. In Lucero, L. J., and Fash, B. W. (eds.), *Precolumbian Water Management: Ideology, Ritual and Power*. Tucson: University of Arizona Press, pp. 223–236.

Scarborough, V. L., 2007. Colonizing a landscape: water and wetlands in ancient Mesoamerica. In Scarborough, V. L., and Clark, J. E. (eds.), *The Political Economy of Ancient Mesoamerica: Transformations during the Formative and Classic Periods*. Albuquerque: University of New Mexico Press, pp. 163–174.

Scarborough, V. L., (ed.), (in press). *Water and Humanity: Historical Overview*. Paris: UNESCO Publishing.

Scarborough, V. L., and Burnside, W. R., 2010. Complexity and sustainability: perspectives from the ancient Maya and the modern Balinese. *American Antiquity*, **75**(2), 327–363.

Scarborough, V. L., and Gallopin, G. G., 1991. A water storage adaptation in the Maya Lowlands. *Science NS*, **251**(4994), 658–662.

Scarborough, V. L., and Isaac, B. L. (eds.), 1993. *Economic Aspects of Water Management in the Prehispanic New World*. Greenwich, CT: JAI Press. Research in Economic Anthropology, Supplement, Vol. 7.

Scarborough, V. L., and Lucero, L. J., 2010. The non-hierarchical development of complexity in the semitropics: water and cooperation. *Water History*, **2**(2), 185–205.

Scarborough, V. L., Schoenfelder, J. W., and Lansing, J. S., 1999. Early statecraft on Bali: the water temple complex and the decentralization of the political economy. *Research in Economic Anthropology*, **20**, 299–330.

Scarborough, V. L., Dunning, N. P., Tankersley, K. B., Carr, C., Weaver, E., Grazioso, L., Lane, B., Jones, J. G., Buttles, P., Valdez, F., and Lentz, D. L., 2012. Water and sustainable land

use at the ancient tropical city of Tikal, Guatemala. *Proceedings of the National Academy of Sciences*, **109**(31), 12408–12413.
Schreiber, K. J., and Lancho Rojas, J., 1995. The puquios of Nasca. *Latin American Antiquity*, **6**(3), 229–254.
Schreiber, K. J., and Lancho Rojas, J., (in press). The filtration galleries of Nasca, Peru: the management of ground water resources from prehistoric time to the present. In Scarborough, V. L. (ed.), *Water and Humanity: Historical Overview*. Paris: UNESCO Publishing.
Sharrock, F. W., Dibble, D. S., and Anderson, K. M., 1961. The creeping dune irrigation site in Glen Canyon, Utah. *American Antiquity*, **27**(2), 188–202.
Shaw, B. D., 1984. Water and society in ancient Maghrib: technology, prosperity and development. *Antiquités Africaines*, **20**, 121–173.
Stargardt, J., 1983. *Satingpra I: The Environmental and Economic Archaeology of South Thailand*. Oxford/Singapore: British Archaeological Reports, International Series 158/Institute of Southeast Asian Studies. Studies in Southeast Asian Archaeology, Vol. 1.
Stephens, J. L., 1843. *Incidents of Travel in Yucatan*. New York: Harper and Brothers.
Tankersley, K. B., and Balantyne, M. R., 2010. X-ray powder diffraction analysis of Late Holocene reservoir sediments. *Journal of Archaeological Science*, **37**(1), 133–138.
Tankersley, K. B., Scarborough, V. L., Dunning, N., Huff, W., Maynard, B., and Gerke, T. L., 2011. Evidence for volcanic ash fall in the Maya Lowlands from a reservoir at Tikal, Guatemala. *Journal of Archaeological Science*, **38**(11), 2925–2938.
Vivian, R. G., 1974. Conservation and diversion: water control systems in the Anasazi Southwest. In Downing, T. E., and Gibson, M. (eds.), *Irrigation's Impact on Society*. Tucson: University of Arizona Press. Anthropological Papers of the University of Arizona, Vol. 25, pp. 95–112.
Walker, J. H., 2008. Pre-Columbian ring ditches along the Yacuma and Rapulo Rivers, Beni, Bolivia: a preliminary review. *Journal of Field Archaeology*, **33**(4), 413–427.
Wilkinson, T. J., 2003. *Archaeological Landscapes of the Near East*. Tucson: University of Arizona Press.
Woodbury, R. B., and Neely, J. A., 1972. Water control systems of the Tehuacan Valley. In Johnson, F. (ed.), *The Prehistory of the Tehuacan Valley. volume 4: Chronology and Irrigation*. Austin: University of Texas Press, pp. 81–161.
Zangger, E., 1994. Landscape changes around Tiryns during the Bronze Age. *American Journal of Archaeology*, **98**(2), 189–212.

Cross-references

Canals and Aqueducts in the Ancient World

X

X-RAY DIFFRACTION (XRD)

Gilberto Artioli
Dipartimento di Geoscienze, Università degli Studi di Padova, Padova, Italy

Synonyms

Bragg diffraction; Bragg scattering; Wave interference from a lattice; X-ray diffraction

Definition

Diffraction: The physical phenomenon of interference produced through the interaction of electromagnetic waves (i.e., X-rays) or particle beams (i.e., electrons, neutrons) with crystals, assumed as atomic lattices.

X-ray diffraction: The diffraction of X-rays by crystals, producing interference effects (i.e., diffracted beams) at specific angles. The geometry of diffraction is described by Bragg's law.

Powder diffraction pattern: The diffraction effects (Debye cones, Debye rings) produced by a polycrystalline powder, that is, a large ensemble of small crystals. The measurements are carried out by powder diffractometry.

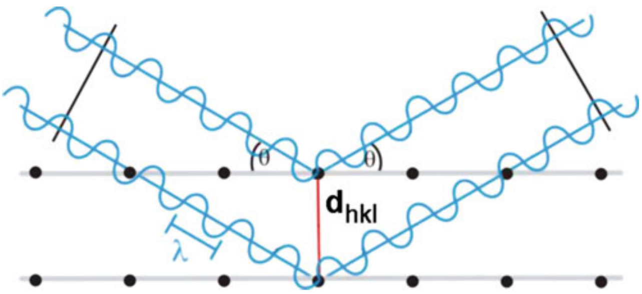
Single-crystal diffraction pattern: The diffraction effects (Bragg spots) produced by an individual crystal, assumed as a coherent crystalline domain having a symmetric, long-range order of atoms. The measurements are carried out by single-crystal diffractometry.

Introduction

Diffraction-based techniques and methods are fundamental tools for the characterization and understanding of materials of quite different nature, including those relevant to investigations in Earth science – e.g., minerals, rocks, sediments, soils, and ore deposits – as well as geoarchaeological explorations of similar materials exploited by humans in the past. X-ray diffraction effects produced by crystals were first observed by Laue and coworkers 100 years ago, and the recent centennial celebrations of 2012 correctly marked the fundamental importance of this discovery (Eckert, 2012; Schmahl and Steurer, 2012). Diffraction techniques developed rapidly during the last century and have become routine tools in the analysis of specific materials in order to inform about (1) phase identification and quantification of crystalline compounds and complex polyphasic mixtures, (2) the texture and orientation of crystalline phases in a material, (3) the atomic and molecular structure of the phases involved, and (4) the physical microstructural state of the material in terms of crystallite size and accumulated strain.

A number of excellent textbooks are available describing the general theory and applications of X-ray diffraction to natural and synthetic compounds (see, e.g., Klug and Alexander, 1974; Warren, 1990; Guinier, 1994; Hammond, 2009; Giacovazzo, 2011). The present focus is the specific contribution of diffraction to geoarchaeological problems. Since geomaterials and other resources of the Earth are fundamental to many aspects of human societies, understanding their provenance, role, and technical uses represents important data for the archaeological interpretation of past cultures (Artioli, 2010). This is especially true for prehistoric times, from which there are no written records to decode human activities, and therefore our comprehension is often limited to the remaining tangible heritage. The analysis of archaeological and geoarchaeological materials by modern diffraction thus serves as an extremely useful tool in understanding the past. Further, the thorough characterization of heritage materials and the processes acting upon them is a mandatory step in heritage management and conservation.

A.S. Gilbert (ed.), *Encyclopedia of Geoarchaeology*, DOI 10.1007/978-1-4020-4409-0,



X-ray Diffraction (XRD), Figure 1 Interference of electromagnetic waves of wavelength λ with crystallographic planes of spacing d_{hkl}. The 2θ diffraction angle satisfying Bragg's law is the one defined by the incident and diffracted beams. The figure shows the case in which Bragg's law is satisfied, i.e., the incoming and diffracted X-rays are in phase, as indicated by the bars joining corresponding peaks and troughs of the two beams. At other angles, the refracted beams would be out of phase to varying degrees and thus would cancel out.

Essential concepts

Among the variety of techniques presently available for the characterization of materials, diffraction is unique insofar as it is intrinsically sensitive to the ordered (i.e., periodic, symmetric) atomic structure of crystals. The diffraction effects produced by the interference of electromagnetic waves and particle beams with matter can be simply and directly related to the properties of the crystal phases present in the system. Figure 1 shows schematically the interference process between monochromatic electromagnetic waves scattered by different atoms in the crystal. Bragg's law

$$2d_{hkl}\sin\theta = n\lambda$$

describes in simple terms the geometric relationship among three factors: (1) the spacing between the atomic planes in the crystal (d_{hkl}), (2) the wavelength of the incident radiation (λ), and (3) the diffraction angle (2θ) – that is, the angle between the incident beam and the diffracted beam. For any given λ, positive interference (i.e., diffraction) occurs only at the angles satisfying Bragg's conditions for all possible atomic planes in the crystal. Each family of atomic planes d_{hkl} has a specific orientation defined by the so-called Miller indices (hkl) with respect to the crystallographic base vectors, which define the crystallographic unit cell, i.e., the lattice, and ensure periodicity in Euclidean space.

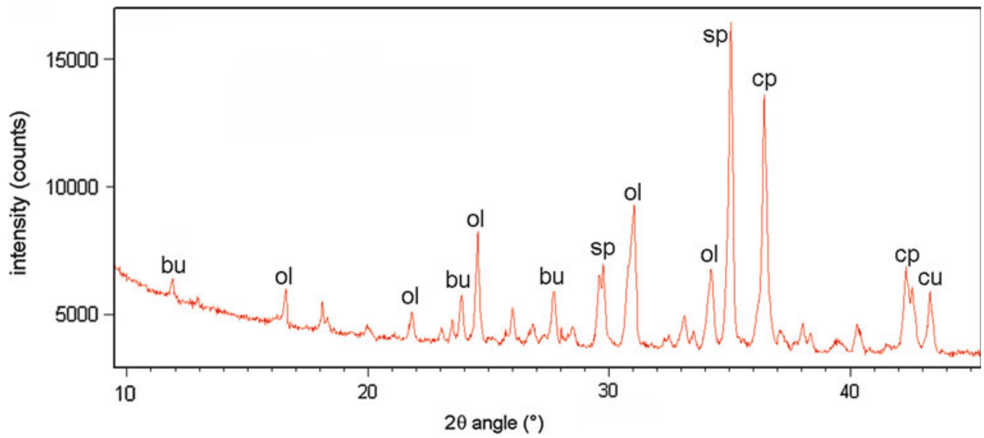
At thermodynamic equilibrium, every solid compound has a specific arrangement of its atoms in space (crystal phase or crystal structure) that minimizes Gibbs free energy, ultimately dictated by the formation of chemical bonds between atoms and molecules. The distinctive crystal structure of each phase at any given pressure and temperature is univocally described by (1) the crystallographic *unit cell*, (2) the *space group symmetry* (see The International Tables of Crystallography, Vol. A: http://it.iucr.org/), and (3) the type and position of each symmetry-independent atom in the unit cell, in terms of *atomic scattering factors* and *positional atomic coordinates*.

Diffraction techniques (Giacovazzo, 2011) in essence yield very basic information on the nature of the material, on its physical state, and on its crystal-chemical arrangement at the atomic and molecular level, providing a means of characterizing and interpreting crystalline compounds from simple elemental and ionic solids to complex macromolecules. The atomic structures of known crystalline compounds are listed in available databases (ICSD: Inorganic Crystal Structure Database, http://www.fiz-karlsruhe.de/icsd.html; CSD: Cambridge Structural Database, http://www.ccdc.cam.ac.uk/products/csd/; MSA-CSD: Mineralogical Society of America Crystal Structure Database, http://www.minsocam.org/MSA/Crystal_Database.html; and others), and they are essential references for identification and analytical purposes.

Concerning the analytical measurements, X-ray single-crystal and powder diffraction techniques are listed among the established and routine tools for the analysis of materials, though one ought not to forget the remarkable recent progress in electron and neutron diffraction. Further, different measurement geometry and instrumentation are required depending on the crystalline nature of the sample. If the sample is monocrystalline (i.e., a single crystal, as most gemmy crystals are), then the diffraction patterns show discrete Bragg diffraction spots derived from the interference of X-rays with the lattice planes. However if the sample is polycrystalline (i.e., the X-ray beam interacts with a large number of randomly oriented crystals), then Bragg's law is satisfied simultaneously by the same lattice plane in many different crystals, and the rotational symmetry of the interference effects produced at each Bragg angle produces a diffraction cone (Debye cones) whose intercept with a flat detector is generally imaged as diffraction rings (Debye rings). This is called *powder diffraction*.

Because of the fact that most geological and archaeological materials are polycrystalline and polyphasic (with the notable exception of gems of course), and because of the inexpensive availability of X-ray sources in scientific laboratories, the preferred diffraction technique universally adopted for analytical purposes of geomaterials is XRPD or X-ray powder diffraction (Klug and Alexander, 1974; Dinnebier and Billinge, 2008; Pecharski and Zavalij, 2009). In its simplest configuration, powder diffractometry scans the reciprocal space and then records an intensity profile as a function of the diffraction angle (Figure 2). The recorded powder pattern corresponds to a one-dimensional section crossing the Debye cones the Debye cones; each measured Bragg peak corresponds to a specific atomic plane of a phase within the sample, and the analysis of the position and intensity of the peaks allows for straightforward identification and quantification of the crystal phases present in the system.

Although it has been used mostly to analyze crystalline compounds, XRD can also be applied to disordered and



X-ray Diffraction (XRD), Figure 2 Example of a measured XRPD pattern obtained from an analyzed sample containing residues of ancient metallurgical activities, including iron-copper ores and smelting slags. Symbols labeling the major Bragg peaks refer to the crystal phases producing those peaks: *bu* bustamite, a calcium manganese silicate, $CaMn^{2+}Si_2O_6$; *ol* fayalitic olivine, an iron silicate, Fe_2SiO_4; *sp* magnetite spinel, an iron oxide, Fe_3O_4; *cu* copper, Cu; *cp* cuprite, a copper oxide, Cu_2O.

amorphous compounds that produce only diffuse scattering (Klug and Alexander, 1974; Guinier, 1994). Furthermore, even materials that are normally considered amorphous, such as glass or vitreous pastes, may contain a significant number of crystal phases that can yield information on their origin and manufacturing techniques (Artioli et al., 2008).

The information ultimately provided by diffraction therefore is related to: (1) phase identification and quantification of crystalline compounds and complex polyphasic mixtures, (2) the texture and orientation of the crystalline phases, (3) the atomic and molecular structure of the phases involved, and (4) the physical microstructural state of the material in terms of crystallite size and accumulated strain. These features will be discussed separately with reference to specific examples.

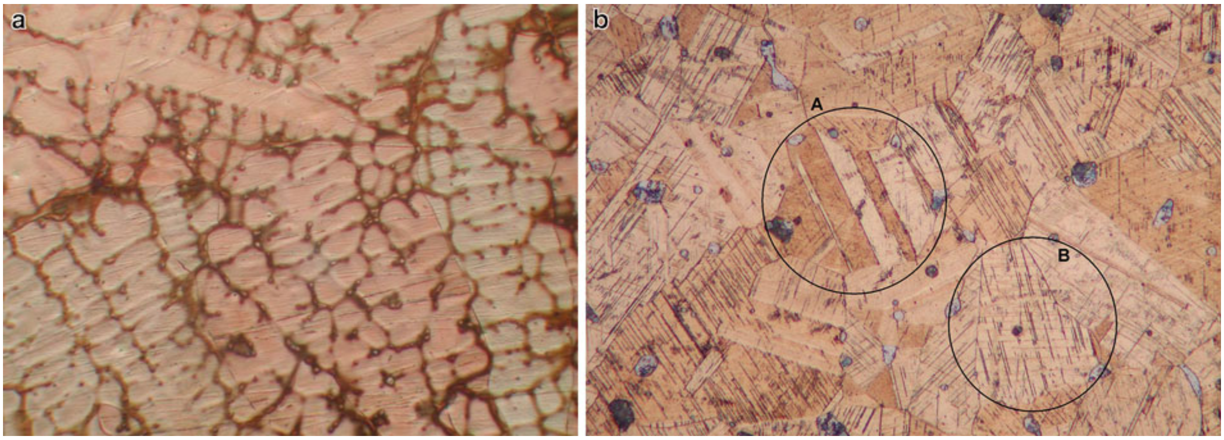
It should be noted that the most advanced method for the modeling and extraction of information from powder diffraction patterns is called *full-profile analysis* (also called *Rietveld analysis* or whole-pattern profile fitting). The method uses a least-squares approach to refine a theoretical line profile until it matches the measured powder diffraction profile (Young, 1993; Dinnebier and Billinge, 2008; Giacovazzo, 2011).

Phase identification and quantification

Any investigation involving Earth materials, or the human-produced artifacts derived from them, necessarily starts with the identification of the chemical system (i.e., chemical analysis) and the identification of the organic and inorganic phases present (i.e., diffraction analysis). Of course by tradition, most mineralogists and petrologists would prefer to carry out analysis by optical microscopy on thin sections or polished sections of the samples, but this depends on the possibility of invasively sampling the material under investigation as well as on the availability of a satisfactory quantity of sample. For many valuable archaeological artifacts, invasive sampling is not possible, so that noninvasive techniques are required. Diffraction is one of these noninvasive means (Artioli, 2013).

Modern laboratory XRPD techniques in fact allow measurements directly on the objects or on minute quantities of material (down to few mg of material) obtained by micro-sampling. The depth of the analysis on an intact object depends crucially on the energy of the probe, on the diffraction geometry, and on the nature of the material. The presence of surface alteration layers, corrosion products, or patinas may substantially influence these measurements, so caution is necessary in interpreting the results. This is especially true when using the new generation of commercial portable probes, designed to perform diffraction measurements in the field or in museums (Chiari, 2008). Some of them adopt the same technology selected for remote measurement that was embodied in the Mars Science Laboratory (MSL CheMin Instrument: Blake et al., 2012). To investigate objects at depth, more penetrating sources should be used, such as neutrons or high-energy synchrotron X-rays.

The reliability and instrumental flexibility of modern diffractometers available in scientific laboratories commonly yields high-quality measured intensity profiles that can be straightforwardly interpreted in terms of phase identification (Figure 2) and quantification, especially if performed through full-profile analysis methods (Madsen and Scarlett, 2008). The diffraction analyses are particularly useful when interpreting complex polyphasic materials, which often comprise tens of mineral phases, such as soils, ceramics, or building materials. Most of these materials – originally composed of clays, carbonates, and other common minerals – have been heavily transformed by human pyrotechnologies, and phases stable at high temperature are now present within



X-ray Diffraction (XRD), Figure 3 Examples of metal textures observed by metallographic analysis in reflected light microscopy: (**a**) copper dendrites in the as-cast metal – a treelike extension of copper crystallization occurring along preferred directions of bonding as the material is allowed to cool slowly; (**b**) thermally recrystallized polyhedral grains in an alpha-bronze metal sample showing features of mechanical working (well-developed slip systems that are the visible effect of the structural dislocations along lattice planes within the material, such as in grain **b**) and thermal annealing (polyhedral grain boundaries and twin planes evidencing individual crystal domains, such as in grain **a**) (Figure 3b courtesy of I. Angelini, University of Padova).

the material. Phase identification is important to reconstruct the firing technology, the oxidation conditions, and the time-temperature path (i.e., the kinetics of the process).

Diffraction experiments can also be performed using special sample-conditioning chambers (to control humidity, oxidizing conditions, etc.) and/or furnaces to attain high temperatures. These measurements yield crucial information on the kinetics of the processes, thereby helping to reproduce ancient technologies (e.g., firing of pottery or faience) or calibrate the rates of alteration or degradation for conservation purposes. Metal corrosion is a specifically important field of investigation for conservation (Leyssens et al., 2005; Adriaens and Dowsett, 2010).

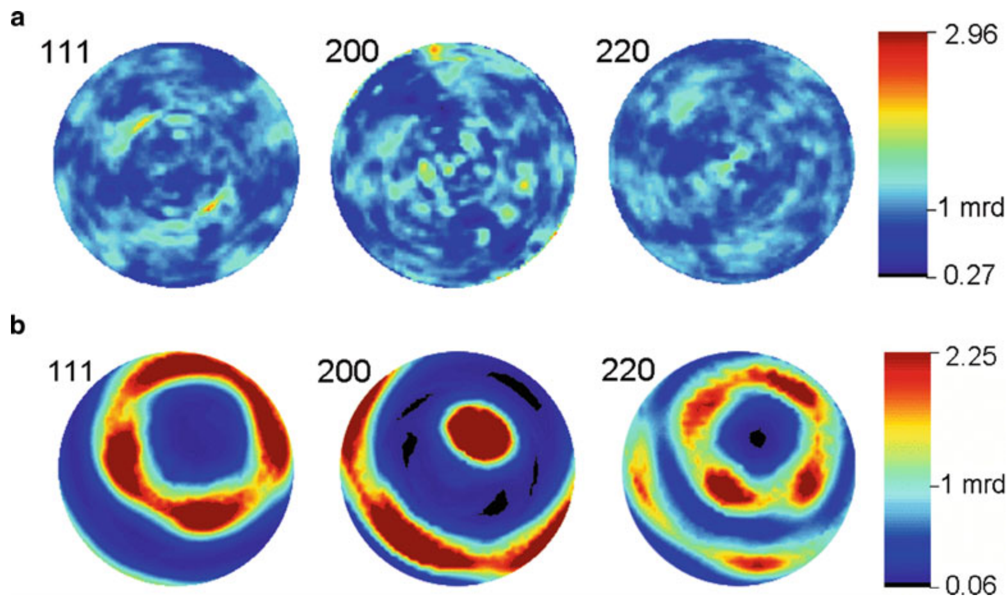
Crystallographic texture analysis

The shape and orientation of crystallites in a solid (i.e., the so-called texture or microtexture) depends on its thermomechanical history. In materials science and engineering, the analysis of the texture is usually performed after the manufacturing of the sample in order to verify and control the produced texture in terms of the shape and size of the grains and their iso-orientation with respect to applied forces. In the analysis of archaeological objects, especially metals, the texture is measured in order to understand and reconstruct ancient manufacturing processes. In archaeometallurgy, this type of analysis is called *metallography* (Scott, 1991), and it is commonly performed by polishing the metal surface, slightly etching that surface to expose the grain boundaries and defects, and then by observing the textural features by reflected light microscopy (Figure 3a, b). Metallography is a powerful tool for interpreting metallurgical processes, its only disadvantage being that sample preparation is invasive and requires several 2D sections at different orientations in order to reconstruct the full 3D texture of the metal.

Diffraction can also be used for texture analysis by measuring and interpreting the nonhomogeneous intensity of Bragg peaks in different directions from the sample, which is related to the nonhomogeneous (i.e., the textured) distribution of crystallites within the sample. The measurement of a substantial number of Bragg intensities along different sample directions allows the recalculation of the orientation distribution function (ODF), which fully describes the statistical crystallographic orientation of the crystals with respect to the sample reference system (Kocks et al., 1998; Popa, 2008). The ODFs are generally visualized by plotting the orientation data in pole figures in sample space (direct space) or in crystallographic space (inverse space) (Figure 4a, b); the units are multiples of the mean random distribution of crystallites. The *crystallographic texture analysis* using diffraction has been proposed as a totally noninvasive metallographic method to interpret the manufacturing of ancient metals, such as prehistoric copper axes (Artioli, 2007), including the well-known 3200 BC copper axe found with the Alpine Iceman mummy, Ötzi (Artioli et al., 2003).

Crystal structure analysis

Despite the fact that X-ray diffraction is the main tool available to investigate crystal structures and derive molecular information, including very complex ones such as proteins and viruses (Giacovazzo, 2011), there is seldom a need to analyze advanced structures in



X-ray Diffraction (XRD), Figure 4 Examples of metal textures measured by crystallographic analysis of neutron powder diffraction data: (**a**) pole figures relative to the (111), (200), and (220) planes of the cast copper shown in Figure 3a. The featureless pole figures are representative of randomly oriented grains, (**b**) pole figures relative to the (111), (200), and (220) planes of the worked metal shown in Figure 3b. The figures show a distinct fiber texture due to the recrystallization of the grains along the working direction. The pole figures are graphical representations of the measured 3D orientation distribution function (*ODF*) of the crystallites along specific sample directions. The color-coded pole figures are in units of mean random distribution (*MRD*), i.e., a sample having the crystallites in a totally random orientation shows a uniform pole figure with MRD = 1 (*blue color*), whereas a sample with preferentially oriented crystallites shows bright colored features in the pole maps.

geo-investigations related to archaeology. As discussed above, the crystal structures and related parameters for mineralogical phases contained with geomaterials are generally taken for granted, and perusal of the existing databases is the major tool for phase identification.

There have been, however, a few cases in which unusual mineral phases were present in materials of cultural interest, e.g., archaeology and art, especially in pigments. In such instances, knowledge of the detailed atomic structure of the phase in question can be of great assistance in understanding the origin of the material, determining its physicochemical properties, and establishing its reactivity. Typical examples are the main crystal phases of two important historical pigments: *Maya blue*, which is an organo-clay hybrid structure composed of indigo partially diffused within the channels of palygorskite clay (Reyes-Valerio, 1993; Sánchez del Río et al., 2011), and *Catalan blue*, which is produced mainly from the pyroxene-related mineral aerinite (Rius et al., 2004).

An interesting example of single-crystal structure analysis using diffraction data applied to archaeological objects is the recent determination of a previously unreported phase of the milarite-osumilite group found in an Egyptian scarab fashioned of glazed steatite (Artioli et al., 2013). This novel phase has a composition different from the other members of the family found in nature, as it was identified as a reaction phase embedded in the contact layer between the surface glaze and the talc body of the scarab. It was formed during the high-temperature application of the glaze, and its structural properties help to define the origin and production process of the object.

Analysis of microstructure

Extraction of information related to the average crystallite size in a polycrystalline sample, and estimation of the presence of lattice strains and defects, is referred to as *physical analysis* or *microstructural analysis* of a sample. It is performed by carefully interpreting the shape and the angle-dependent broadening of the diffraction peaks (Snyder et al., 1999). It is widely used in materials science to assess the residual stress and physical characteristics of industrial and engineering components, since the extracted parameters are directly related to the mechanical and reactivity properties of the materials.

One of the best examples of the application of microstructural analysis to geomaterials of importance in archaeology is the thorough investigation of Egyptian cosmetics carried out by the joint Louvre-CNRS-ESRF group (Martinetto et al., 2001; Ungár et al., 2002). The work was performed mainly using high-resolution X-ray powder diffraction data collected at ESRF (European Synchrotron Radiation Facility), and it analyzed in detail a number of Egyptian kohl samples used in antiquity as eye pigments. The investigation unambiguously showed that the careful mixing of black galena and white pigments (laurionite, hydrocerussite) could produce all shades represented by the observed colors. In addition, the grain size and stress analysis confirmed that galena (large grains, significant accumulated strain) was hand ground from natural sources of the mineral, whereas laurionite and hydrocerussite (small grains, no strain) were certainly produced by chemical precipitation, thus proving the very early production of synthetic cosmetics in ancient Egypt.

Diffraction analysis of bone apatite has also been a popular direction for research, since it has been demonstrated that diagenesis directly influences recrystallization of the mineral phosphate and that the crystallinity of apatite can be measured by XRPD (Hedges, 2002). However, the physicochemical transformations of bone hydroxylapatite during diagenesis are quite complex, involving chemical substitutions, thermal recrystallization, and crystal growth in solution. Therefore, in addition to diffraction measurements, an accurate interpretation of the diagenetic process would likely require complementary investigations, notably by chemical analysis, infrared and Raman spectroscopies, and transmission electron microscopy (see, e.g., Reiche et al., 2003; Piga et al., 2011).

Summary

Diffraction techniques represent a powerful archaeometric tool for investigating all kinds of geomaterials involved in archaeological issues and problems. By selecting the appropriate instrumental configuration and measurement strategies, it is possible to conduct fruitful investigations to characterize the natural materials forming archaeological sites, elucidate the microstratigraphy of layers formed by human activities, determine the sources of raw minerals and rocks employed in the building of architectural components (clays and sand for adobe and bricks, rocks for building stones, carbonates and pozzolanic sands from quarry and fire kilns for mortars and plasters, etc.), examine the properties and evolution of materials collected by humans and transformed by craftsmanship or industrial production into tools, such as flints and cherts into stone implements, ore minerals from mine to metals, clays for pottery and ceramics, etc., and finally investigate in detail archaeological objects in order to understand their nature, properties, and functions, while proposing effective conservation strategies.

Bibliography

Adriaens, A., and Dowsett, M., 2010. The coordinated use of synchrotron spectroelectrochemistry for corrosion studies on heritage metals. *Accounts of Chemical Research*, **43**(6), 927–935.

Artioli, G., 2007. Crystallographic texture analysis of archaeological metals: interpretation of manufacturing techniques. *Applied Physics A*, **89**(4), 899–908.

Artioli, G., 2010. *Scientific Methods and Cultural Heritage: An Introduction to the Application of Materials Science to Archaeometry and Conservation Science*. Oxford: Oxford University Press.

Artioli, G., 2013. Science for the cultural heritage: the contribution of X-ray diffraction. *Rendiconti Lincei, Scienze Fisiche e Naturali*, **24**(Suppl. 1), S55–S62.

Artioli, G., Dugnani, M., Hansen, T., Lutterotti, L., Pedrotti, A., and Sperl, G., 2003. Crystallographic texture analysis of the Iceman and coeval copper axes by non-invasive neutron powder diffraction. In Fleckinger, A. (ed.), *Die Gletschermumie aus der Kupferzeit: 2. Neue Forschungsergebnisse zum Mann aus dem Eis/La mummia dell'età del rame: 2. Nuove ricerche sull'uomo venuto dal ghiaccio*. Bolzano: Folio Verlag, pp. 9–22.

Artioli, G., Angelini, I., and Polla, A., 2008. Crystals and phase transitions in protohistoric glass materials. *Phase Transitions*, **81**(2–3), 233–252.

Artioli, G., Angelini, I., and Nestola, F., 2013. New milarite/osumilite-type phase formed during ancient glazing of an Egyptian scarab. *Applied Physics A*, **110**(2), 371–377.

Blake, D., Vaniman, D., Achilles, C., Anderson, R., Bish, D., Bristow, T., Chen, C., Chipera, S., Crisp, J., Des Marais, D., Downs, R.T., Farmer, J., Feldman, S., Fonda, M., Gailhanou, M., Ma, H., Ming, D.W., Morris, R.V., Sarrazin, P., Stolper, E., Treiman, A., and Yen, A., 2012. Characterization and calibration of the CheMin mineralogical instrument on Mars Science Laboratory. *Space Science Reviews*, **170**(1–4), 341–399.

Chiari, G., 2008. Saving art in situ. *Nature*, **453**(7192), 159.

Dinnebier, R. E., and Billinge, S. J. L. (eds.), 2008. *Powder Diffraction: Theory and Practice*. Cambridge: Royal Society of Chemistry.

Eckert, M., 2012. Disputed discovery: the beginnings of X-ray diffraction in crystals in 1912 and its repercussions. *Acta Crystallographica*, **A68**(1), 30–39.

Giacovazzo, C. (ed.), 2011. *Fundamentals of Crystallography*, 3rd edn. Oxford: Oxford University Press.

Guinier, A., 1994. *X-ray Diffraction in Crystals, Imperfect Crystals, and Amorphous Bodies*. New York: Dover Publications.

Hammond, C., 2009. *The Basics of Crystallography and Diffraction*, 3rd edn. Oxford: Oxford University Press.

Hedges, R. E. M., 2002. Bone diagenesis: an overview of processes. *Archaeometry*, **44**(3), 319–328.

Klug, H. P., and Alexander, L. E., 1974. *X-ray Diffraction Procedures for Polycrystalline and Amorphous Materials*, 2nd edn. New York: Wiley.

Kocks, U. F., Tomé, C. N., and Wenk, H.-R. (eds.), 1998. *Texture and Anisotropy: Preferred Orientations in Polycrystals and Their Effect on Materials Properties*. Cambridge: Cambridge University Press.

Leyssens, K., Adriaens, A., Dowsett, M. G., Schotte, B., Oloff, I., Pantos, E., Bell, A. M. T., and Thompson, S. P., 2005. Simultaneous in situ time resolved SR-XRD and corrosion potential analyses to monitor the corrosion on copper. *Electrochemistry Communications*, **7**(12), 1265–1270.

Madsen, I. C., and Scarlett, N. V. Y., 2008. Quantitative phase analysis. In Dinnebier, R. E., and Billinge, S. J. L. (eds.), *Powder Diffraction: Theory and Practice*. Cambridge: Royal Society of Chemistry, pp. 298–331.

Martinetto, P., Anne, M., Dooryhée, E., Drakopoulos, M., Dubus, M., Saloman, J., Simionovici, A., and Walter, P., 2001. Synchrotron X-ray micro-beam studies of ancient Egyptian make-up. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, **181**(1–4), 744–748.

Pecharsky, V. K., and Zavalij, P. Y., 2009. *Fundamentals of Powder Diffraction and Structural Characterization of Materials*, 2nd edn. New York: Springer.
Piga, G., Santos-Cubedo, A., Brunetti, A., Piccinini, M., Malgosa, A., Napolitano, E., and Enzo, S., 2011. A multi-technique approach by XRD, XRF, FT-IR to characterize the diagenesis of dinosaur bones from Spain. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **310**(1–2), 92–107.
Popa, N. C., 2008. Microstructural properties: texture and macro stress effects. In Dinnebier, R. E., and Billinge, S. J. L. (eds.), *Powder Diffraction: Theory and Practice*. Cambridge: Royal Society of Chemistry, pp. 332–375.
Reiche, I., Favre-Quattropani, L., Vignaud, C., Bocherens, H., Charlet, L., and Menu, M., 2003. A multi-analytical study of bone diagenesis: the Neolithic site of Bercy (Paris, France). *Measurement Science and Technology*, **14**(9), 1608–1619.
Reyes-Valerio, C., 1993. *De Bonampak al Templo Mayor: El azul maya en Mesoamérica. Colección América Nuestra 40*. México: Siglo XXI Editores.
Rius, J., Elkaim, E., and Torrelles, X., 2004. Structure determination of the blue mineral pigment aerinite from synchrotron powder diffraction data – the solution of an old riddle. *European Journal of Mineralogy*, **16**(1), 127–134.
Sánchez del Río, M., Doménech, A., Doménech-Carbó, M. T., Vázquez de Agredos Pascual, M. L., Suárez, M., and García-Romero, E., 2011. The Maya blue pigment. In Galán, E., and Singer, A. (eds.), *Developments in Palygorskite-Sepiolite Research: A New Outlook on These Nanomaterials*. Oxford: Elsevier. Developments in Clay Science, 3, pp. 453–481.
Schmahl, W. W., and Steurer, W., 2012. Laue centennial. *Acta Crystallographica*, **A68**(1), 1–2.
Scott, D. A., 1991. *Metallography and Microstructure of Ancient and Historic Metals*. Los Angeles: The Getty Conservation Institute.
Snyder, R. L., Fiala, J., and Bunge, H.-J. (eds.), 1999. *Defect and Microstructure Analysis by Diffraction*. Oxford: Oxford University Press.
Ungár, T., Martinetto, P., Ribárik, G., Dooryhée, E., Walter, P., and Anne, M., 2002. Revealing the powdering methods of black makeup in Ancient Egypt by fitting microstructure based Fourier coefficients to the whole x-ray diffraction profiles of galena. *Journal of Applied Physics*, **91**(4), 2455–2465.
Warren, B. E., 1990. *X-ray Diffraction*. New York: Dover Publications.
Young, R. A., 1993. *The Rietveld Method*. Oxford: Oxford University Press. International Union of Crystallography Monographs on Crystallography, Vol. 5.

Cross-references

Archaeological Stratigraphy
Archaeomineralogy
Artifact Conservation
Ceramics
Chemical Alteration
Glass
Landscape Archaeology
Lithics
Metals
Microstratigraphy
Ötzi, the Tyrolean Iceman
Pigments
Soils

X-RAY FLUORESCENCE (XRF) SPECTROMETRY IN GEOARCHAEOLOGY

M. Steven Shackley
Geoarchaeological XRF Laboratory, Department of Anthropology, University of California, Berkeley, CA, USA

Introduction

> X-ray fluorescence is now a well established method of analysis both in the laboratory and industry. The fact that the method is essentially non-destructive makes it particularly attractive for the analysis of archaeological and museum artifacts.... Due to certain fundamental characteristics of the technique it is not suitable for some projects which would seem at first sight to present no problems. (Hall, 1960)

Edward Hall's abstract for his 1960 paper entitled "X-ray fluorescent analysis applied to archaeology" in the journal *Archaeometry* is just as appropriate one-half century later. X-ray fluorescence (XRF) spectrometry may be more "well established" today, yet it is still "not suitable for some projects" even though it might seem so, and many archaeologists might wish that it would be so. This entry presents a brief discussion of the applicability of XRF analysis in archaeology. A number of recent published works on this subject delve into great depth and are highly recommended for further edification (e.g., Beckhoff et al., 2006; Potts and West, 2008; Shackley, 2011a; and the important Jenkins, 1999).

XRF has traditionally been conducted within a laboratory using desktop instrumentation, but currently, the market is flooded with many portable X-ray fluorescence (PXRF) instruments that can be taken directly to the field for immediate results. Do the portable devices really do all that their marketing suggests (see Shackley, 2011b; Speakman et al., 2011)? This question represents a watershed issue in the current practice of XRF spectrometry. The recent edited volume by Potts and West (2008) is devoted to the portable instrument and its applications in science and engineering, including archaeological stone and museum works of art, and more recently Ioannis Liritzis and Nikolaos Zacharias (2011) have provided a critical evaluation of PXRF in obsidian studies as well as other archaeological materials. The question for many excavators is whether there remains a need for the desktop laboratory EDXRF (energy-dispersive X-ray fluorescence spectrometer). Can the less expensive instrument that gives instant results in outside-laboratory settings serve just as well? It may be too soon for a definitive answer, but newer versions of PXRF instruments and software may be resolving some of these issues.

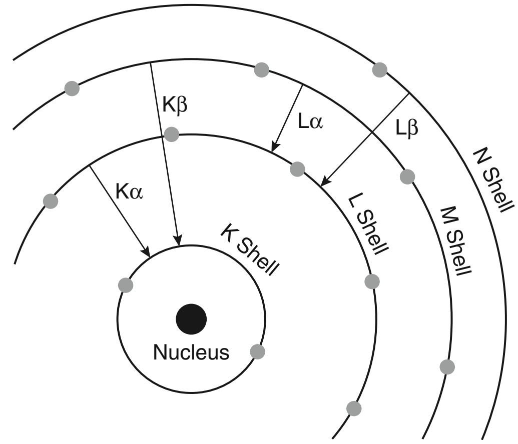
The vast majority of archaeological XRF worldwide is applied to inorganic materials, mainly volcanic rocks, and there are very good technical reasons (see Davis et al., 2011; Lundblad et al., 2011). This does not dismiss the potential value of analyzing ceramics or organics

(Speakman et al., 2011). Pottery is a mixture of rocks and clay sediments that lends itself to XRF analysis (Neff, 1992; Hall, 2001; Pollard and Heron, 2008). The difference is that volcanic rocks are formed at very high temperatures in the earth's mantle or crust, and they possess a geochemical uniformity within local rock bodies that helps match artifactual samples to their natural sources; ceramics show far greater variability in many ways, including composition and manufacture, which is a direct reflection of their human production, and thus sourcing pottery sherds, while commonly done, incorporates more complications.

Today provides a very different picture from Edward Hall's XRF world; archaeology as a discipline has changed markedly, both theoretically and methodologically, due in large part to the cultural insights and technologies that are available in the twenty-first century. Issues of social identity, equality, gender, national character, and native rights are all current and important concerns in archaeology today, but they are being addressed with the use of these new tools – XRF certainly among them (see Sillar and Tite, 2000; Pollard and Bray, 2007; Joyce, 2011; Mills et al., 2013). Scholars have argued that our twenty-first-century archaeological tools have offered broader and deeper perspectives on human behavior because the new data combined with evolving questions yields a process of inquiry much improved over previous decades (Shackley, 2005; see also Joyce, 2011). X-ray fluorescence spectrometry will continue to play an important role in illuminating the past. What XRF will look like in another 50 years is impossible to imagine, but the rise of the portables is perhaps a glimpse into that future.

History of XRF in archaeology

X-rays were discovered by the German physicist Wilhelm C. Röntgen (1845–1923), for which he won the Nobel Prize in 1901 (Röntgen, 1898). In 1909, Charles G. Barkla found a connection between X-rays radiating from a sample and the atomic weight of the sample. In 1913, Henry G. J. Moseley helped number the elements with the use of X-rays, by observing that the K line transitions – or primary transitions from one electron orbit to another – in an X-ray spectrum moved the same amount each time the atomic number increased by one, a primary theoretical precept in XRF physics (Moseley, 1913, 1914; see Figure 1 here). He is credited with revising the periodic tables, which were based on increasing atomic weight, to periodic tables based on atomic number. He later laid the foundation for identifying elements in X-ray spectroscopy by establishing a relationship between frequency (energy) and the atomic number, a fundamental basis of X-ray spectrometry. The potential of the technique was quickly realized, with half of the Nobel Prizes in physics awarded to developments in X-rays from 1914 to 1924.

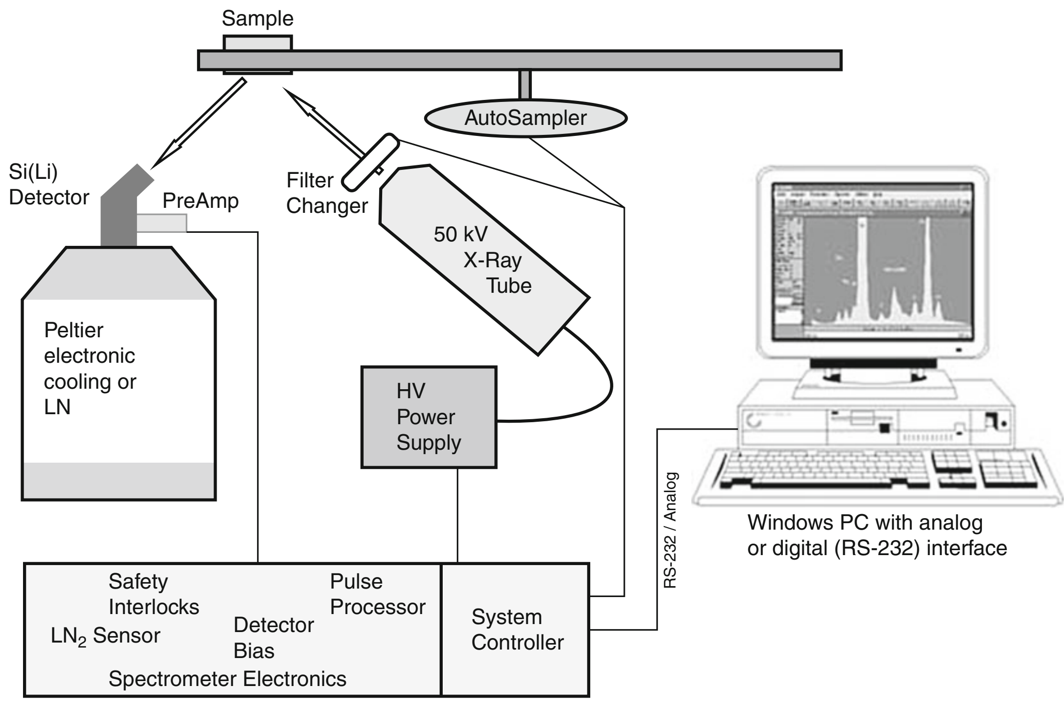


X-ray Fluorescence (XRF) Spectrometry in Geoarchaeology, Figure 1 Schematic view of orbital transitions due to X-ray fluorescence (From Shackley, 2011b: Figures 2-1). This graphic shows the orbital movement (transitions) of electrons subjected to high-energy X-rays in a typical sample. Electrons that are removed from their orbital position can move into other atoms, but when an electron returns to an orbital position, that X-ray energy creates an energy that is measured by the XRF system. The Kα transition is the most energetic and easily measured by today's XRF instruments. The Kα transition requires the greatest input energy to occur and thus creates the greatest energy (fluorescence) that is most easily measured by modern detectors.

A brief discussion of the principles of XRF

In EDXRF analysis, samples are irradiated with photons, usually from an X-ray tube or radioisotopic source. The primary X-ray beam excites electrons in the sample, causing the atoms in the sample to emit secondary X-rays, i.e., to *fluoresce*. The emitted X-rays occur at energies specific to elements in the sample, appearing as peaks over a given energy spectrum (Figure 1). The height or *intensity* of a given peak reflects, in part, the concentration of that element in the sample, and this amplitude may be converted to units of concentration, usually by comparison to a regression line or quadratic algorithm based on well-characterized standards (McCarthy and Schamber, 1981; Jenkins, 1999).

Traditional XRF analysis of geologic samples is destructive to the sample and requires rigorous and time-consuming sample preparation. Samples are ground to a fine powder and pressed into briquettes or, for analysis of major elements, prepared as fused glass disks, particularly for wavelength XRF (WXRF), where the relationship between the angle of the instrument and the object analyzed is crucial. However, with energy-dispersive XRF (EDXRF), the surface of the object is not as critical to success because the emitted energy is captured by the detector for all elements simultaneously, and through the detector and multichannel analyzer, that energy is converted to pulses that the software ultimately translates into elemental data (Davis et al., 2011; Figure 2 here). Figure 2 is



X-ray Fluorescence (XRF) Spectrometry in Geoarchaeology, Figure 2 Schematic drawing of a typical EDXRF instrument. Cooling can be either electronic Peltier or liquid nitrogen (LN), and many of the more recent instruments use more sensitive detectors than Si/Li (From Shackley, 2011b: Figures 1-9).

a schematic view of a typical EDXRF instrument, commonly used today, including many of the portable instruments, although the Si/Li detectors are now being replaced by detectors with greater sensitivity. Early EDXRF instruments did not yield the instrumental precision of WXRF, but neutron activation analysis (NAA), advances in detector electronics, and improved software have decreased the differences between these instruments. Miniaturization has ultimately heralded the portable XRF technology currently emerging (see Liritzis and Zacharias, 2011). A number of experiments (summarized in Davis et al., 2011) have shown that EDXRF is the most effective technique in the analysis of volcanic rocks when sample destruction is not possible (see also Lundblad et al., 2008).

The overarching assumption seems to be that XRF, and particularly energy-dispersive X-ray fluorescence (EDXRF) spectrometry, solves many of our problems in compositional analysis and geochemical sourcing. Glascock (2011) recently addressed this issue by directly comparing the results of NAA versus EDXRF for obsidian sources in central Mexico.

What's good about XRF?

The appeal of X-ray analysis of archaeological specimens lies in its remarkable combination of practical and economic advantages:

1. XRF is nondestructive. In the vast majority of cases, analyzed samples are not destroyed or changed by exposure to X-rays. They can thus be saved for future reference or used for other types of testing that may be destructive, such as obsidian hydration analysis.
2. There is minimal preparation. Many samples can be examined with little or no pretreatment, including almost all obsidian artifacts. While it is best to wash any sediments off archaeological specimens, it has been shown that if the dirt is minimal and the artifact has not been subjected to heat so high as to melt some sediment matrix onto the sample, vigorous cleaning is not necessary (Shackley and Dillian, 2002). This is mainly due to the penetration of X-rays in the mid-Z X-ray region – the region of the periodic table that contains elements from approximately $Z = 22$ (titanium) to $Z = 41$ (niobium) and generally does not require instrument chamber vacuum for analysis – beyond the surface, and while it does incorporate any contamination on the surface, it is generally not an issue if some soil remains in the flake scars. The analyzed volume is very large compared to any surface contamination. This is not the case with most metals, where patination and chemical weathering can radically change the composition at the surface and yield erroneous results (Hall, 1960).

3. XRF is fast. X-ray spectrometry enables chemical compositions to be determined in seconds. For an analysis of the elements Ti through Nb on the Berkeley Spectrace and Thermo desktop instruments, at 200 live seconds per sample, it takes about 5–6 min per sample depending on mass. More recent detectors can acquire these data even more rapidly.
4. XRF is easy to use. Modern instruments run under graphical interfacing software that easily handles measurement setup and results calculation. Tasks that once required the constant attention of a trained analyst can now be handled by skilled students and are fully automated after effective calibration and method compilation.
5. XRF is cost effective. Without the more involved sample preparation necessary in most WXRF and all destructive analyses, the cost is significantly lowered per sample.

While these advantages suggest that XRF will solve all our problems, it is not the panacea many would like it to be (Speakman et al., 2010).

What nondestructive EDXRF will not do

Sample size limits

Samples >10 mm in the smallest dimension and >2 mm thick are optimal for EDXRF analyses (see Lundblad et al., 2008; Davis et al., 2011). This is important because, as Shackley (1990) and more recently Eerkens et al. (2007) noted for hunter-gatherers in the North American West, high residential mobility often requires that stone sources, including obsidian, be conserved for long periods of time. As an example, an Archaic hunter will attempt to rejuvenate a dart point rather than make a new one whenever possible while moving through the landscape. The rejuvenation of that point creates debitage that is quite small, often smaller than 10 mm. With modern recovery techniques, these small fragments of debitage are retrieved much more often than they were in the past, and Eerkens et al. (2007) found that indeed these small obsidian flakes in North American Great Basin sites indicated not only greater distance to the original raw material used in toolmaking, but they indicated also a greater diversity of sources than was visible using only the analysis of larger flakes with EDXRF. So, while EDXRF can analyze much of the stone material left in prehistory, it may not solve all problems of interest to twenty-first-century archaeologists. To be fair, however, the procurement ranges that could be reconstructed were relatively accurate using samples above the 10 mm threshold in the Eerkens et al. (2007) study, and the smaller flakes were analyzed using NAA, which is essentially a destructive technique. Recently, however, newer digital EDXRF instrumentation and tube collimation have extended sample size ranges down to 2 mm with the Thermo Scientific Quant'X EDXRF at Berkeley.

Restricted elemental acquisition

As discussed below, nondestructive XRF is restricted generally to a subset of the mid-Z X-ray region, which is the best portion (including the Ti-Nb range) and contains excellent elements for the analysis of volcanic rocks (Shackley, 2005). While some rare-earth elements, those with low atomic numbers, or those possessing very low concentrations can be useful in discriminating sources, in most cases XRF cannot resolve their concentrations. This is discussed in detail in Glascock's (2011) comparison between XRF and NAA.

XRF cannot characterize small components

XRF like NAA is a mass analysis: every component in the irradiated substance is included in the analysis. It is possible to collimate the incoming x-rays from the tube and/or into the detector to focus on small components such as various minerals, but environmental scanning electron microscopy (ESEM), electron microprobe, or laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS) is much better suited to this kind of analysis. However, the bulk analysis of volcanic rocks has been shown to be quite effective.

XRF will not solve all problems in archaeological provenance studies, but it is simply the best nondestructive analytical tool available at this time.

Is PXRF a revolution or just the latest development in XRF?

While portable XRF has both become very popular and highly criticized, this should be expected in a discipline that borrows much of its analytical technology (Liritzis and Zacharias, 2011; McAlister, 2011; Shackley, 2011a, b; Sheppard et al., 2011; Speakman and Shackley, 2013). What seems most problematic is that portable instruments were originally designed for mining and industrial applications and sought only qualitative results. Such methods and calibrations are neither necessary nor sufficient to address archaeological problems, where relatively precise quantitative data are required. Tied to this, most of the instruments, unlike lab/desktop EDXRF, have not allowed users to generate their own calibrations, and indeed, most relied solely on fundamental parameter routines that are often standardless and could not be modified beyond factory settings. The criticisms have had their effect, and many manufacturers are generating software that allows the user to employ linear calibrations by ratioing peaks/counts to the Compton scatter, a physical artifact of X-ray fluorescence, and thus eliminate the problem of differing sample sizes as earlier discussed by Davis et al. (2011) and Lundblad et al. (2008) for lab EDXRF instruments (for a detailed discussion of the Compton scatter, see Shackley, 2011b: 211). Given these important shifts in the ability of PXRF, it will be possible to take a sensitive instrument to field or museum settings and nondestructively analyze at least volcanic rocks with an instrumental precision and accuracy similar to those of lab XRF instruments. Most of the PXRF systems now available do not acquire the range of elements that laboratory systems do – i.e., sodium (Na) through uranium (U) – but the mid-Z (i.e., $Z = 22–41$) sensitivity seems to be very good. There may come a time in the near future when portable systems will acquire the typical sodium through uranium elements that laboratory instruments can today, but they are not here yet. This is likely in the future of XRF applications to archaeology. It is anticipated that archaeologists will evaluate it with dispassionate skepticism and use it in ways that yield useful information.

Bibliography

Beckhoff, B., Kanngießer, B., Langhoff, N., Wedell, R., and Wolff, H. (eds.), 2006. *Handbook of Practical X-Ray Fluorescence Analysis*. New York: Springer.

Davis, M. K., Jackson, T. L., Shackley, M. S., Teague, T., and Hampel, J. H., 2011. Factors affecting the energy dispersive x-ray fluorescence (EDXRF) analysis of archaeological obsidian. In Shackley, M. S. (ed.), *X-Ray Fluorescence Spectrometry (XRF) in Geoarchaeology*. New York: Springer, pp. 45–63.

Eerkens, J. W., Ferguson, J. R., Glascock, M. D., Skinner, C. E., and Waechter, S. A., 2007. Reduction strategies and geochemical characterization of lithic assemblages: a comparison of three case studies from Western North America. *American Antiquity*, **72**(3), 585–597.

Glascock, M. D., 2011. Comparison and contrast between XRF and NAA: used for characterization of obsidian sources in central Mexico. In Shackley, M. S. (ed.), *X-ray Fluorescence Spectrometry (XRF) in Geoarchaeology*. New York: Springer, pp. 161–192.

Hall, E. T., 1960. X-ray fluorescent analysis applied to archaeology. *Archaeometry*, **3**(1), 29–35.

Hall, M. E., 2001. Pottery styles during the early Jomon period: geochemical perspectives on the moroiso and ukishima pottery styles. *Archaeometry*, **43**(1), 59–75.

Jenkins, R., 1999. *X-Ray Fluorescence Spectrometry*, 2nd edn. New York: Wiley.

Joyce, R. A., 2011. Is there a future for XRF in twenty-first century archaeology? In Shackley, M. S. (ed.), *X-ray Fluorescence Spectrometry (XRF) in Geoarchaeology*. New York: Springer, pp. 193–202.

Liritzis, I., and Zacharias, N., 2011. Portable XRF of archaeological artefacts: current research, protocols and limitations. In Shackley, M. S. (ed.), *X-ray Fluorescence Spectrometry (XRF) in Geoarchaeology*. New York: Springer, pp. 109–142.

Lundblad, S. P., Mills, P. R., and Hon, K., 2008. Analysing archaeological basalt using non-destructive energy-dispersive X-ray fluorescence (EDXRF): effects of post-depositional chemical weathering and sample size on analytical precision. *Archaeometry*, **50**(1), 1–11.

Lundblad, S. P., Mills, P. R., Drake-Raue, A., and Kekuewa Kikiloi, S., 2011. Non-destructive EDXRF analyses of archaeological basalts. In Shackley, M. S. (ed.), *X-ray Fluorescence Spectrometry (XRF) in Geoarchaeology*. New York: Springer, pp. 65–80.

McAlister, A. J., 2011. *Methodological Issues in the Geochemical Characterisation and Morphological Analysis of Stone Tools: A Case Study from Nuku Hiva, Marquesas Islands, East Polynesia*. Unpublished Ph.D. dissertation, University of Auckland.

McCarthy, J. J., and Schamber, F. H., 1981. Least-squares fit with digital filter: a status report. In Heinrich, K. F. J., Newbury, D. E., Myklebust, R. L., and Fiori, C. E. (eds.), *Energy Dispersive X-ray Spectrometry: Proceedings of a Workshop on Energy Dispersive X-ray Spectrometry Held at the National Bureau of Standards, Gaithersburg, MD, 20760, April 23–25, 1979*. Washington, DC: US Government Printing Office. National Bureau of Standards Special Publication 604, pp. 273–296.

Mills, B. J., Clark, J. J., Peeples, M. A., Haas, W. R., Jr., Roberts, J. M., Jr., Hill, J. B., Huntley, D. L., Borck, L., Breiger, R. L., Clauset, A., and Shackley, M. S., 2013. Transformation of social networks in the late pre-Hispanic US Southwest. *Proceedings of the National Academy of Sciences*, **110**(15), 5785–5790.

Moseley, H. G. J., 1913. High frequency spectra of elements. *Philosophical Magazine, Series 6*, **26**(156), 1024–1034. **27**(160), 703–713.

Moseley, H. G. J., 1914. High frequency spectra of elements. Part II. *Philosophical Magazine, Series 6*, **27**(160), 703–713.

Neff, H. (ed.), 1992. *Chemical Characterization of Ceramic Pastes in Archaeology*. Madison: Prehistory Press. Monographs in World Archaeology, Vol. 7.

Pollard, A. M., and Bray, P., 2007. A bicycle made for two? The integration of scientific techniques into archaeological interpretation. *Annual Review of Anthropology*, **36**, 245–259.

Pollard, A. M., and Heron, C., 2008. The geochemistry of clays and provenance of ceramics. In Pollard, A. M., and Heron, C. (eds.), *Archaeological Chemistry*, 2nd edn. Cambridge: Royal Society of Chemistry, pp. 98–145.

Potts, P. J., and West, M. (eds.), 2008. *Portable X-ray Fluorescence Spectrometry: Capabilities for In Situ Analysis*. Cambridge: The Royal Society of Chemistry.

Röntgen, W. C., 1898. Ueber eine neue Art von Strahlen: Zweite Mitteilung [On a new kind of rays: second communication]. *Annalen der Physik*, **64**, 12–17.

Shackley, M. S., 1990. *Early Hunter-Gatherer Procurement Ranges in the Southwest: Evidence from Obsidian Geochemistry and Lithic Technology*. Unpublished PhD dissertation, Tempe, Arizona State University.

Shackley, M. S., 2005. *Obsidian: Geology and Archaeology in the North American Southwest*. Tucson: University of Arizona Press.

Shackley, M. S. (ed.), 2011a. *X-ray Fluorescence Spectrometry (XRF) in Geoarchaeology*. New York: Springer.

Shackley, M. S., 2011b. An introduction to X-ray fluorescence (XRF) analysis in archaeology. In Shackley, M. S. (ed.), *X-ray Fluorescence Spectrometry (XRF) in Geoarchaeology*. New York: Springer, pp. 7–44.

Shackley, M. S., and Dillian, C., 2002. Thermal and environmental effects on obsidian geochemistry: experimental and archaeological evidence. In Loyd, J. M., Origer, T. M., and Fredrickson, D. A. (eds.), *The Effects of Fire and Heat on Obsidian*. Denver: U.S. Department of the Interior, Bureau of Land Management. Cultural Resources Publication, pp. 117–134.

Sheppard, P. J., Irwin, G. J., Lin, S. C., and McCaffrey, C. P., 2011. Characterization of New Zealand obsidian using PXRF. *Journal of Archaeological Science*, **38**(1), 45–56.

Sillar, B., and Tite, M. S., 2000. The challenge of 'technological choices' for materials science approaches in archaeology. *Archaeometry*, **42**(1), 2–20.

Speakman, R. J., and Shackley, M. S., 2013. Silo science and portable XRF in archaeology: a reply to Frahm. *Journal of Archaeological Science*, **40**(2), 1435–1443.

Speakman, R. J., Phillips, S. C., Florey, V., Little, N. C., and Iñañez, J. G., 2010. *Approaches to micro-XRF analysis of obsidian*. Paper presented at the 38th international symposium on archaeometry, University of South Florida, Tampa.

Speakman, R. J., Little, N. C., Creel, D., Miller, M. R., and Iñañez, J. G., 2011. Sourcing ceramics with portable XRF spectrometers? A comparison with INAA using Mimbres pottery from the American Southwest. *Journal of Archaeological Science*, **38**(12), 3483–3496.

Y

YORK

Maria-Raimonda Usai
Dipartimento di Architettura, Design e Urbanistica,
Università di Sassari, and University of York, UK

Definition

York (53°57′30″N; 1°4′49″W) is a city in northern England. It is situated on a well-drained east–west ridge (the "York Moraine") comprising deposits of the last Ice Age that crosses a low-lying NE-SE belt of land, the Vale of York, which was shaped by glaciers and surrounded by hills to the east and west. The moraine formed an easy route through the wet vale and became both a place for settlement and a defensive position for a succession of prehistoric and later invaders and occupants.

The region's landscape and water resources attracted prehistoric peoples, with Neolithic, Bronze, and Iron Age finds recorded from sites on the moraine, its lower slopes, and surrounding areas and peat bogs (Hall, 1996, 27; Neal and Roskams, 2012). Analysis of waterlogged organic-rich sediment dated to c. 1100 BC indicated that the land was then interspersed with shallow pools of water and that animal husbandry was practiced nearby (Hall, 1996, 66).

York itself was founded by the Romans in AD 71 on a relatively flat area of the moraine on a wedge of land between and to the north of the confluence of the major river (Ouse) and its tributary (Foss). They employed banks of earth and turf to build a 20-ha legionary timber fortress, which became the core of *Eboracum* [York] (Hall, 1996, 27–28). On the opposite side of the Ouse, the slope was significantly more pronounced, and when Roman civilian developments took place here in the late second century, the greater interventions for drainage and land stability this required had a stronger impact on the landscape. This is expressed archaeologically by layers of turf and clay-rich sediments forming terraces to counteract the natural slope, and by ditches dug in the second century (Hall, 1996, 31).

Lack of datable sediments from the fifth-century York makes interpretation of the post-Roman to early medieval periods uncertain. Thus, *dark earth* materials in York are rare: they were only observed below York Minster and in two areas of the ancient Roman *Colonia*, in the form of dark grayish-brown sediments postdating Roman deposits (Usai, 1999, 2001). Micromorphological characteristics of such deposits from the *Colonia* area included rare bone fragments, excrement features, and ash inclusions in only some of the examples, while all contexts contained charcoal fragments and were characterized by a low degree of mixing, with the rare traces of biological activity or postdepositional weathering suggesting the possibility of rapid burial at both sites (Usai, 1999, 2001). These deposits have been seen as having only limited similarities to stratigraphically analogous contexts elsewhere in Britain (Macphail, 1980, 1987).

Excavations in Coppergate, just to the south of the area of the Roman fortress, revealed an up to 8 m thick sequence of complex stratified deposits with a basal layer of yellow sandy clay cut by Roman features (Hall, 1996, 27–28). The latest Roman remains were covered by up to 85 cm of light gray loamy soil, representing the post-fifth-century period (and possibly spanning the period to the ninth century) with no trace of occupation. It was suggested that such soil was either brought in from elsewhere or formed by gradual accumulation of windblown silts (Kenward and Hall, 1995). The overlying deposits within the 8 m sequence enclosed vestiges of carefully planned properties with building plots and fence lines and a large accumulation of up to 3 m of exceptionally organic-rich sediments and debris, containing wood and bark fragments (including chips), from the building of

A.S. Gilbert (ed.), *Encyclopedia of Geoarchaeology*, DOI 10.1007/978-1-4020-4409-0,

wooden structures and woodworking activities, along with the dumping of large quantities of dye-bath waste from textile working. Pit fills often largely consisted of human fecal matter, again with excellent preservation of delicate biological remains (Kenward and Hall, 1995). These highly organic deposits provided evidence for occupation that was resumed in the later ninth century by York's Viking occupants after 400 years with little activity (Hall, 1995; Kenward and Hall, 1995). The locally intense waterlogging conditions accounted for excellent organic preservation within the sediments, the material accumulating at a faster rate than it decayed, resulting in a rapid rising of the local ground level by up to 2 cm/year (Hall, 1996, 71). The sediments have been described as having compost-like consistence and "as 'water-retaining sponges' but not being usually saturated – yet often wet or merely damp" (Kenward and Hall, 2006). In particular, they preserved substantial remains of the ground plans of a series of timber buildings on four tenement plots. Investigation of plant and insect remains within the "sponge" materials yielded abundant evidence for living conditions, craft, and other activities in this area from the late ninth to late eleventh centuries while shedding light on the way the deposits had been formed (Kenward and Hall, 1995). Patches of the richly organic materials extended for 200 or 300 m laterally from the Coppergate area into the heart of the town, with areas of poorer preservation appearing to have resulted from recent decay (Kenward and Hall, 2000).

There are few geoarchaeological records for the late eleventh to early thirteenth centuries of Norman York. These consist mainly of sediments from a large pool of sluggish water (the King's Pool) generated by damming the River Foss. The works revealed no sedimentation within the pool during the late eleventh to thirteenth centuries, and this was attributed to regular cleaning of the pool for fish farming (Hall, 1996, 73).

Parts of York, along the gentler upper slopes of the Ouse and close to the Foss – particularly near the perimeter of the King's Pool and often overlying Roman deposits on river slopes – preserve layers of sediments exceptionally rich in organic material that act as "water-retaining sponges" (Kenward and Hall, 2006). The areas apparently formed from stable manure in the second- to third-century deposits, and more dramatically again in the Viking period (Allan Hall, pers. comm.). It has been suggested that standing walls, clay banks, and other archaeological features of Roman and later date may have acted as barriers to lateral water flow (Kenward and Hall, 2006).

The accumulation of organic-rich sediments becomes increasingly more restricted from the Norman to medieval period. In a sense, time is compressed in York's medieval stratification: very thin sediment layers close to the surface may represent several hundred years, whereas the same thickness of earlier deposits might represent decades (Hall, 1996, 79).

Many Roman and most Norman, medieval, and later stone buildings, including the city walls and Minster (cathedral), use the beautiful, easily worked, Permian magnesian limestone from outcrops to the southwest of the city (Buckland, 1977). The building stones of Roman York were mainly Carboniferous grit, sandstone, shale, and coal (Usai, 2005, 7); however, Jurassic sandstones and even Pleistocene volcanic erratics were employed for a minority of Roman and other buildings (Buckland, 1977).

Acknowledgements

The author thanks Allan Hall for his comments and the cited unpublished information.

Bibliography

Buckland, P. C., 1977. Building stones. In Whitwell, J. B. (ed.), *Church Street Sewer and an Adjacent Building. In the Legionary Fortress. The Archaeology of York*. York: Council for British Archaeology, Vol. 3, fasc. 1.

Hall, R., 1995. Archaeological introduction. In Kenward, H. K., and Hall, A. R. (eds.), *Biological Evidence from Anglo-Scandinavian Deposits at 16–22 Coppergate. The Archaeology of York*. York: Council for British Archaeology, Vol. 14, fasc. 7.

Hall, R. A., 1996. *English Heritage Book of York*. London: B. T. Batsford/English Heritage.

Kenward, H. K., and Hall, A. R., 1995. *Biological Evidence from Anglo-Scandinavian Deposits at 16–22 Coppergate. The Archaeology of York*. York: Council for British Archaeology, Vol. 14, fasc. 7, pp. 435–797.

Kenward, H. K., and Hall, A., 2000. Decay of delicate organic remains in shallow urban deposits: are we at a watershed? *Antiquity*, **74**(285), 519–525.

Kenward, H., and Hall, A. R., 2006. Easily-decayed organic remains in urban archaeological deposits: value, threats, research directions and conservation. In Brinkkemper, O., Deeben, J., van Doesburg, J., Hallewas, D. P., Theunissen, E. M., and Verlinde, A. D. (eds.), *Vakken in vlakken. Archeologische kennis in lagen*. Amersfoort: Rijksdienst voor het Oudheidkundig Bodemonderzoek. Nederlandse Archeologische Rapporten, Vol. 32, pp. 183–198.

Macphail, R. I., 1980. *Soil report on the "dark earth" from the Bedern excavation at York*. Ancient Monuments Laboratory Reports 3061.

Macphail, R. I., 1987. *Soil report on Redfearns Glassworks York*. Ancient Monuments Laboratory Reports 112.

Neal, C., and Roskams, S., 2012. Prehistory at Heslington East; an interim assessment. *Prehistoric Yorkshire*, **49**, 61–64.

Usai, M. R., 1999. *Fetter lane, York: dark earth?* Reports from the Environmental Archaeology Unit, York, 99/26.

Usai, M. R., 2001. *Station rise: dark earth?* Reports from the Environmental Archaeology Unit, York, 01/11.

Usai, M.-R., 2005. *Geoarchaeology in Northern England I. The Landscape and Geography of Northern England*. Portsmouth: English Heritage. Center for Archaeology Reports Series, Vol. 54.

Z

ZHOUKOUDIAN

Chen Shen
Royal Ontario Museum, Toronto, ON, Canada

Synonyms

Choukoutien (Wade-Giles romanization system); 周口店 (in Chinese)

Definition

Zhoukoudian, a small township located on the outskirts of present-day Beijing (China), is named for its 27 Pleistocene hominin and/or faunal fossil sites. These include Locality 1 cave where the *Homo erectus* fossils (aka Peking man) were recovered in 1929 and subsequent years. It is one of the UNESCO World Heritage sites of China inscribed in 1987.

Zhoukoudian is located in the Fangshan District, 55 km southwest of downtown Beijing. A hill called *Longgushan*, “Dragon Bone Hill,” was known by local farmers in the early twentieth century for quarrying of Ordovician limestone. Zhoukoudian was first visited by the Swedish geologist Johan Gunnar Andersson as a potential location for finding Quaternary mammalian fossils in 1918. The American paleontologist Walter Granger later identified fossils at Dragon Bone Hill in 1921. Austrian paleontologist Otto Zdansky then discovered three *Homo erectus* teeth from Locality 1 cave prior to 1926, the year Canadian anthropologist Davidson Black named the hominin teeth as a new species: *Sinanthropus pekinensis*. Black secured funding from the Rockefeller Foundation and started the official international collaboration with the Cenozoic Research Laboratory (today’s Institute of Vertebrate Paleontology and Paleoanthropology, Chinese Academy of Sciences) in 1927. Both Black and Chinese paleontologist Yang Zhongjian led excavations at the site, where the first skull of a Peking man was recovered by Chinese anthropologist Pei Wenzhong (aka W.C. Pei) in 1929. Since 1930, Zhoukoudian has become one of the most important paleoanthropology sites for the study of human evolution in the world.

Zhoukoudian includes 27 localities of hominins, faunal, and cultural remains, with the latest one – Tianyuandong Cave – identified in 2001. Four of these locations yielded significant hominin fossils of different species. From Locality 1 cave (the Peking man site), 203 fragments of *Homo erectus* belonging to more than 40 individuals were recovered. These included six nearly complete skulls, five of which were lost during WWII (Figure 1). The Peking man skulls are the most important study subjects for Asian *Homo erectus* and have been published extensively. A human premolar unearthed at Locality 4 in 1973 was unknown to the world; it probably belongs to Asian archaic *Homo sapiens*. Locality 26 (the Upper Cave) yielded 10 individual fossil remains belonging to modern human *Homo sapiens sapiens*, which are also well-studied specimens in paleoanthropology. The latest discovery of human fossils at Zhoukoudian was from the Tianyuandong Cave, where 34 fragments were found, including a mandible, teeth, and postcranial bones, which represent a nearly complete individual (Shang and Trinkaus, 2010). Direct AMS ^{14}C dating from a limb fragment produced the most reliable and earliest date for China’s *Homo sapiens sapiens* at Zhoukoudian, ranging from 42,000 to 38,500 years ago. Recent studies further identified evidence indicating that the Tianyuandong hominin might have worn shoes. Carbon and nitrogen isotope analysis of the samples suggest human consumption of freshwater fish at Zhoukoudian 40,000 years ago.

The most focused studies at Zhoukoudian have been dating, climatic context, lithic technology, and hominin and carnivore remains of Locality 1 cave. Recent dating

A.S. Gilbert (ed.), *Encyclopedia of Geoarchaeology*, DOI 10.1007/978-1-4020-4409-0,

Zhoukoudian, Figure 1 The author examined the only surviving Peking man skull fragment at the Institute of Vertebrate Paleontology and Paleoanthropology, Chinese Academy of Science, in Beijing in 2010.

studies have changed the old perspectives about when Peking man lived, suggesting that he may have appeared at Zhoukoudian as early as 780,000 years ago (Shen et al., 2009), when the world was experiencing extreme cold and dry climates. With cultural material deposits measuring 40 m deep, it is possible to show the occupation of early hominins may have lasted half a million years at Zhoukoudian. Lithic artifacts were recovered from deposits of three cultural phases (early layers 8–10, middle layers 6–7 and QII, and late layers 3–5), accounting for more than 17,000 artifacts in total. These were cataloged into 10 classes with 40 types of stone tools, which suggest a gradual transition from simple use to a more complicated tool manufacturing process at the site (Zhang, 2004). The lithic artifacts from Locality 15 (dated to the late Middle Pleistocene and early Late Pleistocene periods) reveal evidence suggesting that lithic technology at the site was more developed than that of their predecessors at Locality 1. The Zhoukoudian Locality 15 hominin (most likely East Asian *Homo heidelbergensis* although no fossils have been recovered yet) effectively mastered sophisticated core reduction modes, represented by multidirectional flaking and alternate flaking, which were not evident at Locality 1.

Locality 13 was first excavated in 1933–1934 and re-excavated in 1956–1957. The stone tools recovered here were first considered to be within the East Asian "chopper-chopping tool" tradition in the original conceptualization of the Movius line, an apparent line proposed by Hallam Movius in 1948 that separated handaxe-using cultures of

Zhoukoudian, Figure 2 The recent excavation at the western profile walls of Zhoukoudian Locality 1 cave site in 2009.

western Eurasia from non-handaxe-using ones to the east. However, later studies suggest some of the chopper tools in early reports should be reclassified as cores instead. There is no chronometric date from the site, but comparative faunal dates and sediment stratigraphy suggest that this locality is possibly the earliest hominin occupation at Zhoukoudian.

One of the debated issues about Zhoukoudian's cultural contents surrounds the use of fire. Although there are no structurally defined hearths at the Locality 1 site, burnt ashes, charcoal, burnt bones, and even stone tools were often identified in situ. Whether or not these fire-related activities were the result of intentional human control and manipulation or due to natural causes and hydraulic transport is the subject of further studies. Since 2009, full-scale excavations at the Locality 1 site have been carried out by Chinese scientists and have revealed possible fire floors in layer 4 (Figure 2). An interdisciplinary research team is taking samples for all relevant scientific testing with the expectation that the results will advance our knowledge about the human use of fire in the Middle Pleistocene at Zhoukoudian.

Bibliography

Shang, H., and Trinkaus, E., 2010. *The Early Modern Human from Tianyuan Cave, China*. College Station: Texas A&M University Press. Texas A&M University Anthropology Series, Vol. 14.

Shen, G., Gao, X., Gao, B., and Granger, D. E., 2009. Age of Zhoukoudian *Homo erectus* determined with $^{26}Al/^{10}Be$ burial dating. *Nature*, **458**(7235), 198–200.

Zhang, S., 2004. *The Peking Man Ruins Annals*. Beijing: Beijing Press.

Author Index

A.S. Gilbert (ed.), *Encyclopedia of Geoarchaeology*, DOI 10.1007/978-1-4020-4409-0,

Subject Index

A.S. Gilbert (ed.), *Encyclopedia of Geoarchaeology*, DOI 10.1007/978-1-4020-4409-0,