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Lawrence B. Conyers

Ground-penetrating Radar and Magnetometry for Buried Landscape Analysis

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ISSN 2211-4165 ISSN 2211-4173 (electronic)
SpringerBriefs in Geography
ISBN 978-3-319-70889-8 ISBN 978-3-319-70890-4 (eBook)
https://doi.org/10.1007/978-3-319-70890-4

Library of Congress Control Number: 2017958570

Printed on acid-free paper

This Springer imprint is published by Springer Nature
The registered company is Springer International Publishing AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Preface

For more than a decade, archeologists and cultural geographers have appreciated how important it is to place ancient people into their cultural and natural environment. When sites can be studied in this context, people's adaptation to environmental factors, changes in those environments, and human interactions with each other can become part of a holistic examination of human behavior. This has fostered the subfield of landscape archeology, which takes into consideration not just artifacts and features left behind by past people, but analyzes them within their overall environmental context. When important remains of human activity and aspects of the ancient landscape and environment are buried and no longer visible at the surface, geophysical analysis becomes an obvious choice for this type of large-scale analysis.

Two commonly used landscape-scale geophysical techniques are magnetometry and ground-penetrating radar (GPR). Magnetometry gained an early recognition for these types of studies as the instruments can be moved across broad areas quite readily, producing large-scale images of features within the upper few meters of the ground surface. This is a passive method that measures changes in the earth's magnetic field and is especially useful for the discovery and mapping of ditches and berms, large structures, and other features of the built environment, especially those that have been burned, or contain ferrous objects. As magnetometry instruments are extremely sensitive, even small changes in the amount of organic matter, which is often very slightly magnetic, can be mapped over large areas producing dramatic images of buried cultural and natural landscapes. In this way, large-scale constructions such as ditches, property boundaries, and other built features are visible. GPR data are somewhat slower to collect as the antennas that transmit and receive radar waves must be kept in contact, or very near, the surface. The GPR method, however, is capable of a three-dimensional analysis of buried layers as long as the interfaces between those buried units and objects reflect energy. While the properties of the materials in the ground are important to understand what is visible in GPR images, the GPR method is usually not capable of determining much about the composition of those specific materials. An integration of GPR and magnetometry is therefore symbiotic, as the results of one technique can readily inform interpretations made with the other, and vice versa.

Most magnetometry and GPR results are often displayed in map view, allowing for a visual analysis of differences in the ground that may be the result of buried features of interest. In ground that is suitable for one or the other method, these images can often be highly informative, displaying striking large-scale maps of buried features. However, in many cases, map images are less distinct, with some features effectively invisible for reasons that can often remain obscure. A common interpretation method is to overlay, or directly compare GPR and magnetometry maps of the same area, looking for common trends of buried anomalies, or perhaps direct correlations. While this comparison of results derived from the two techniques can sometimes yield good results, a different interpretation technique is presented here. It begins with an analysis of individual GPR reflection profiles over small two-dimensional slices within a larger study area to identify buried strata that can be interpreted using standard GPR techniques. Then, individual magnetic readings are extracted from a larger dataset and compared directly to the GPR profiles, helping to define the composition of the features that are visible with GPR. A variation on this method is to look for important features visible in magnetic maps and then use GPR profiles to determine what about the units in the ground is producing those magnetic readings. Both these types of direct comparisons can be applied in an iterative way, gaining even more utility by correlation to known units visible in excavations or outcrops.

This type of initial small-scale GPR and magnetic interpretation can begin in just a corner of a larger grid of data, and those results become a way to understand what it is about the various units in the ground that are providing the contrasts visible with each technique over the larger area. When this is done, both small- and large-scale features become understandable, and the origins of all can be mapped spatially using both methods in conjunction. The images produced from both GPR and magnetometry therefore become less "anomaly maps" and more "geophysically defined feature maps," displaying understandable and more readily interpretable images of buried materials that make up buried landscapes.

At a Roman site in Croatia, the buried walls of a structure were readily visible in the magnetic map, but invisible using GPR. At this site, the stones that had been used for building the house walls had mostly been recycled in the past, and only the foundations of the building, visible as composition changes were imaged with magnetics. In contrast, buried Roman structures in England could be readily mapped using GPR, as much of the stones were still in place and readily reflected radar energy. There was not enough magnetic contrast in the buried architecture at this site to be readily visible in the magnetic maps. In Ireland, magnetic mapping defined roads, ditches, and property boundaries in a buried village associated with a Medieval castle. The GPR profiles clearly defined house floors and other stone features associated with living structures, with the magnetic readings being useful for interpreting which areas had been burned, and where the central hearths of houses were located. A seventeenth-century English farmstead in Connecticut associated with a Native American village was discovered using GPR mapping, as the house cellars and other structures filled with homogeneous sediment were readily visible in amplitude maps. The magnetic maps over the large study area were cluttered with anomalies produced from recent metal trash and were almost useless in mapping the buried farming village. However, individual magnetic readings, when compared to the GPR profiles, showed which houses had been burned and where metal objects were located. At a 6000-2000 year old hunter-gather site in Colorado magnetic mapping was capable of locating hearths and ovens, which are invisible in GPR images as they were small in size and compositionally too similar to the surrounding ground. The GPR profiles were quite effective at locating packages of sediment deposited during different environmental changes in this dynamic landscape over millennia, and therefore, the subtle features left by these mobile people, and their artifacts, could be placed within that changing ancient landscape.

The overall purpose of this book therefore is to recommend methods not commonly employed in geophysical landscape analysis where small areas of larger grids are analyzed first using both GPR and magnetometry. Only when an understanding of what each method is capable of measuring regarding the specific properties of materials in the ground can the larger features in the landscape-scale maps generated by each method be more readily defined and interpreted.

Denver, USA Lawrence B. Conyers

Acknowledgements

A great deal of thanks goes to my wonderful friends and colleagues who were so generous in supplying me with their very large and complex datasets of magnetics and GPR. Those collaborators are Fabian Welc and Radoslaw Mieszkowski of University of Warsaw, Poland; Kris Lockyear, University College, London; Maeve Herrick and Jasmine Saxon, my students from University of Denver, Sam Connell, Foothill College, Los Altos, California; Niall Brady, Dublin, Ireland; Dan Cearley, Las Positas College, Livermore, California; and Ken Kvamme, University of Arkansas. Involved in all those projects were numerous hardworking colleagues who collected the data, helped process, and interpret it and as with all field projects, worked long hours to produce excellent datasets. Those workers and collaborators include Brian Jones, Brianna Delessandro, Maeve Herrick, Jasmine Saxon, Brandon Ackermann, Shayleen Ottman, Michele Koons, Mark Mitchell, and Rolfe Mandel. Very many thanks also go to Jarrod Burks and Ken Kvamme for consultation and mentoring in magnetic analysis and David Wilbourn for data processing.

Contents

Chapter 1
Introduction

Abstract Artifacts, architecture and other remains of human use and adaptations to environmentally-defined landscapes are generally termed cultural landscapes. These are often buried and difficult to find and study, especially over broad areas. Geophysical tools, when accompanied by and correlated to information obtained from excavations is one way to expand knowledge of human activities over these large areas. Ground-penetrating radar can produce images in two and three-dimensions that define geological and anthropogenic units and features if those materials in the ground generate radar reflections from layer surfaces. The composition and extent of those materials is often discernable using magnetometer analysis, as that method produces images and discrete measurements of differences in the magnetic properties of some of the units that reflect radar energy. If the two methods are merged and evaluated in small areas first, where much can be determined about units and features of interest, this information can be projected over a wide area in order to understand broad natural landscapes and human activities in the past that occurred on and within them.

1.1 Introduction

This book presents methods and interpretations on how two commonly used near-surface geophysical techniques can be used in conjunction. The goal of this methodological integration is to study historic and prehistoric human uses of and adaptations to past environments and buried landscapes. These two methods are ground-penetrating radar (GPR) and magnetometry, which produce complementary but not directly correlative analyses of materials preserved in the ground. The GPR method produces three-dimensional images of complex layers of sediment and soil, and often architectural and other human-produced materials within those layers. The magnetic method measures changes in the Earth's magnetic field as a function of the magnetic properties of materials in the ground. It is only indirectly a three-dimensional method, but complementary with GPR as it can often determine the composition of buried materials, which is difficult with most GPR analyses. By

L. B. Conyers, *Ground-penetrating Radar and Magnetometry for Buried Landscape Analysis*, SpringerBriefs in Geography,
https://doi.org/10.1007/978-3-319-70890-4_1

incorporating and then interpreting these two techniques in conjunction it is possible to map both the extent of cultural landscapes, now buried below the ground surface, and the types of both natural and anthropogenic materials within those ancient deposits.

1.2 Geophysics for Landscape Analysis

Archaeological analyses of past landscapes has developed and become broader over the last few decades to include many disciplines and multiple methods that allow for placing ancient or historic people and their cultures into environments (Butzer 1971). While geological and paleo-environmental analysis of sediments and soils is crucial to these studies, integration of those analyses with excavation information and sometimes historical accounts (Bruno and Thomas 2008) has been a focus for studying people over larger areas in the past. The use of geophysics in these studies is one of many methods that has been increasingly used, especially when much of the buried materials of interest are hidden from view (Campana and Piro 2008; Kvamme 2003). A history, critique and outlook of the future of using geophysics for landscape archaeology was initially proposed by Kvamme (2003) where he stressed the ability of geophysics to map broad areas and collect high-density grids of information about buried landscapes and the cultural features within. In the early 21st century a variety of geophysical methods began to be increasingly used by researchers in these endeavors as a way to evaluate larger areas than was possible using traditional excavation methods. The dominant geophysical interpretative analysis for many years has been a visual analysis of geophysical anomalies and patterns visible in map view using deductive reasoning largely with an analysis of shapes (Keay et al. 2014; Kvamme 2006). Those shapes might be circles, squares or other “cultural anomalies” that are unlikely to be found in nature and are therefore more likely to be human-caused. A commonly employed analogy to this type of geophysical interpretation is aerial photo interpretation as those usually contain a plethora of shapes and patterns, just as geophysical maps.

Early in the history of using geophysics for landscape-scale analysis it was appreciated that multiple geophysical methods would be necessary in order to more completely understand what the produced maps are showing about buried landscapes (Kvamme 2001; Piro et al. 2000). These early studies concluded that archaeological geophysics’ major contribution to understanding buried landscapes was its ability to produce maps of broad areas identifying settlements or human-caused patterns that might have existed there in the past. This is done by identifying the remains of dwellings, streets, lanes, trails, plazas, possible trash dumping areas, middens, mounds, garden spaces, storage features, fortifications and a large variety of other potentially important architectural elements not visible on the surface (Campana and Piro 2008). In this approach geophysics was seen as a powerful method to directly study people from their architectural-scale remains within past environmental contexts through the production of geophysical imagery.

Landscape-scale geophysical studies for the most part employ magnetics, electrical induction and resistivity for very large scale analysis and ground-penetrating radar using its three-dimensional abilities in smaller grids (Conyers 2006; Johnson 2006). This has recently changed as multiple GPR antenna arrays can collect huge datasets over broad landscapes (Gaffney et al. 2012; Trinks et al. 2010). Two or more geophysical methods was always considered optimum for larger-scale studies of landscapes and researchers quickly understood the necessity of integrating large amount of data from multiple sources (Johnson and Haley 2004; Kvamme 2006; Kvamme et al. 2006; Campana et al. 2009).

1.3 Multiple Method Integration

The geophysical community has been working for more than a decade on methods to integrate two or more geophysical methods, usually focused on presenting processed data in map-view and visually interpreting both (Campana et al. 2009; Gallo et al. 2009; Verdonck et al. 2009). The simplest and most common method of multiple method integration is a superimposition of multi-layer maps followed by a visual interpretation those results (Johnson and Haley 2004; Gallo et al. 2009). This visual method can often be quite beneficial for large-scale interpretation, especially when the cultural features of interest are close to the ground surface, not complicated by geological variations and the buried architecture is distinct (Kvamme 2003). Some have taken interpretations to a higher level using quantitative methods that allow multiple sensor maps to be integrated digitally. This approach often analyzes anomalies produced in maps (or what are colloquially knows by some as "hot spots") using statistical "overlays" within Geographic Information Systems (GIS) or using a variety of other spatial statistics in what are called "data fusion methods" (Sarris et al. 2013; Keay et al. 2014; Kvamme et al. 2006). These types of quantitative analyses allow for the production and analysis of correlation coefficients, principle components analysis, regression, knowledge-based systems and other approaches that evaluate "co-occurrence" of geophysical anomalies with a statistical production of the more valid correlations regarding locations of buried features.

This approach was always seen as somewhat problematic even by its proponents as it was understood that each geophysical method is producing "anomalies" that may or may not have anything at all to do with anomalies produced in maps using a different method (Kvamme 2006). It was noted by many that for data fusion to be successful the geophysical anomalies must be first defined, understood and then a local knowledge of what kinds of buried archaeological features might exist and their geological matrix is necessary (Kvamme et al. 2006). Many data fusion attempts were often bedeviled by producing graphical overlays of large scale maps using multiple methods that produced products that were often "busy" and therefore time-consuming to interpret. This interpretative limitation was addressed using a variety of graphical overlay techniques such as assigning anomalies values on color scales, for instance RGB analysis where an additive color model is used to assign red, green and blue colors to various values of geophysical anomalies, which are added together in assigned ratios in order to produce a broad array of other colors that visually signify correlations. Other methods used translucent overlays of anomalies that also produce dizzying arrays of colors assigned to the anomalies produced by different geophysical methods, all visible in map view.

All these attempts to analyze very complex maps of anomalies (with each method producing anomalies in very different ways for very different reasons) can often be overwhelming. Ultimately, conclusions based on an interpretation of these methods of data fusion, no matter what the statistical correlations, often revolve around a visual analysis of results in map view. This approach was always somewhat confusing to me, and in my own research I often found that with GPR mapping areas where no anomalies were produced often were more important to the identification of buried cultural features (Conyers 2011). This book is an attempt to overcome this complexity by first looking at the basic data produced by two methods, GPR and magnetometry, as a way to define the origin of the features visible in map view prior to attempting to visually interpret the multiple method complexity of anomalies over large areas. In this way interpretation of the larger maps of broad landscape features is a secondary product conducted only after an analysis of geological stratigraphy, buried archaeological features and other aspects of the "anomaly generation process" is conducted.

1.4 The Focus of This Book: A Modification from Other Approaches to Integrate Methods

My geophysical archaeology background has, until a few years ago, been almost wholly in the application of ground-penetrating radar (Conyers 2012, 2013, 2016). In the last few years I began to apply magnetic data by working with magnetism experts (Becker 2015; Burks and Cook 2011; Creekmore 2010; Kvamme 2003; Lockyear and Shlasko 2016) who use magnetometers much of the time in their research and who have generously shared with me their knowledge of acquisition, processing and interpretation in a way that lowered my "learning curve". Here I have relied on their expertise and in some cases their datasets for integration with GPR and applied it to buried landscape analysis.

In the past (and likely for the near future) my magnetometry-focused colleagues are quickly and efficiently able to point out anomalies in their magnetic maps and make interesting comments about whether they are iron objects, ditches, possibly cultural features, and expound on the origin and even orientation of many features that are visible to them, if not to novice interpreters. This kind of knowledge in magnetic-map interpretation comes with a good deal of experience, and this ability becomes even more important when large datasets are integrated with excavations and the origin of mapped features can be understood (Kvamme et al. 2006).

Kris Lockyear, who has a variety of huge geophysical projects underway at a number of buried sites north of London, England is always showing me amazing magnetic maps from Roman and other age sites (Lockyear and Shlasko 2016). He and his colleagues are using multiple sensors to evaluate landscape-sized areas, mostly concentrating on magnetics and electrical resistivity, with GPR in selected areas. Their ability to see otherwise invisible buried features using the resulting images is very impressive. As a learning experiment Kris Lockyear lent me a very robust dataset covering an 80 × 80 m area at the Roman town of Durobrivae, in Cambridgeshire, UK. His magnetic maps impressively show the locations at this buried town where there were commercial streets and associated buildings (pottery production was prominent here during Roman time), and many other architectural features including a possible enclosure with a central religious temple (Fig. 1.1). Large scale and detailed maps of this sort are particularly impressive when much about the buried site becomes immediately visible with a great deal of geophysical field work, data processing and ultimately map production. A cursory examination of the magnetic map in Fig. 1.1 from this site shows possible walled enclosures, some local areas of very high magnetism, which are areas that were likely places of intense burning in the past, and some buildings along what might have been streets.

I asked Kris if I could take his datasets that include both magnetics and GPR collected over the same grid and process both using my own methods. When I processed the GPR reflection profiles into standard amplitude slice-maps, one depth-slice image shows a variety of high amplitude reflections that generally mimic those visible in the magnetic map (Fig. 1.1). What appear to be walls on the east of the grid were probably commercial buildings along streets that show up in the GPR amplitude map as distinct high amplitude walled buildings. There is a

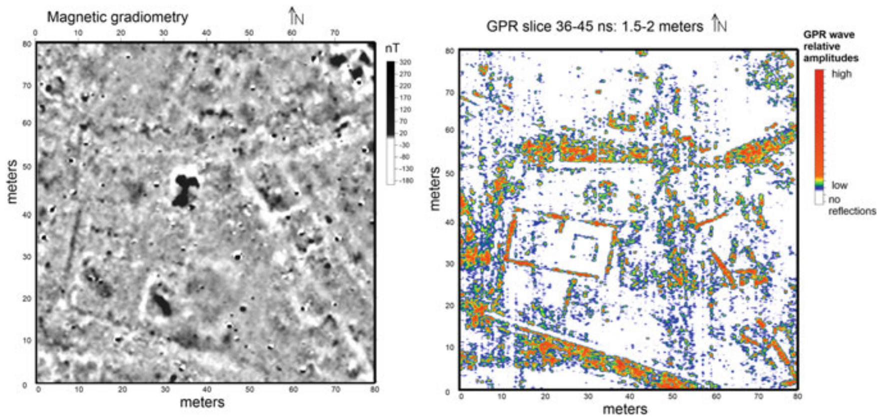

Fig. 1.1 Magnetic anomaly map and GPR amplitude map from the Roman Age Dubrobrivae site, England, showing some linear magnetic anomalies, large highly magnetic areas and small dipoles in the magnetic map. The GPR map from one slice at 1.5–2 m depth displays a few of the same features as the magnetic map, but there is little direct correlation of features

central enclosure, which is hypothesized to be a temple complex, which is also distinctly visible.

When the two maps (magnetic and one GPR slice-map) were overlaid so that a direct correlation could be made, it was interesting that there is almost no one-to-one spatial correlation of the magnetic features to those produced with GPR. While they mostly align with regard to the linear features, it was sometimes the positive magnetic anomalies that were the best correlation to the GPR reflections, and in other places the negative ones. In other locations in this grid magnetic anomalies were "offset" some distance from the GPR-mapped buried features. When this same visual analysis was done using shallower GPR depth-slices there were a variety of other GPR features that have no magnetic "signature". Also, the reverse occurred where magnetic anomalies had no "visibility" using only the GPR amplitude maps. While no spatial statistics was performed using GIS tools, the simple "map overlay" method showed a general similarity, but one that was not at all perfect, with many spatial variations that could not be readily explained.

This project showed me what others have no-doubt long understood: GPR and magnetic imagery can be complementary in some ways, but as the two techniques are not always producing anomaly maps of the same properties of buried materials, they will rarely "match up". Instead, each method is producing images of certain materials, which may or may not relate to those being produced by the other method (Gaffney and Gater 2003).

After more than a year of personal research making analyses of GPR and magnetic maps, I came to the conclusion that perhaps there might be a different way to compare the results of these two methods other than comparing them in map view, as is the traditional technique. This book is a result of that work, and I present here a different method, not widely used, which can potentially be used to merge and integrate datasets for an understanding of buried cultural landscapes. While the data fusion methods employed by others still hold great promise in batch processing large multiple datasets, I think it is important to first understand what is creating the images from each technique before allowing computer algorithms to take over analyses. Often when confronted with complexity of the sort, which is common in geophysical maps, I revert to the "old school" method of basic data analysis. It analyzes small amounts of data from very small areas first as an attempt to understand what about the ground is producing those readings (Conyers 2015). Only then do I usually feel confident to interpret larger scale regions. In general that is the approach that is used in the integrated method discussed here for landscape analysis.

Sometimes each and every data point (or a few of them collected sequentially) can yield information about the ground that can increase understanding (Conyers 2015). My personal history in geophysics began in a time when we had no computer ability to efficiently make large-scale maps (Conyers 2012) and we therefore had to make all interpretations manually from paper images. I was therefore overjoyed with the computer processing power and software that allowed us to go beyond the drudgery of looking at all data on a small scale and attempting to make interpretations about large areas with what were then unwieldy data sets (Conyers 1995).

What has happened with the increase in computer power over the last decades is both powerful and empowering in that we can now process huge datasets over landscape-size grids quickly, but at the risk of losing important information of great value (Conyers 2015). There is a trend in geophysical archaeology to always go directly from the raw data collected in the field immediately to the large-scale maps of the areas of interest. With data fusion methods that merge and compare multiple large data sets, even more basic data is "processed out" or filtered away in these processes.

What is presented here is a reversion to an analysis of the individual data first, before the large-scale analysis is performed. This is because when maps of large areas are produced, individual magnetic readings are filtered, averaged, interpolated between, and then gridded to produce images. With GPR amplitude maps relative reflection amplitudes, usually collected in profiles, are re-gained, re-sampled in slices, often filtered and processed in other ways, and finally interpolated between and re-gridded before a final map is produced. Both of those important data manipulation procedures are important to produce maps and while basic information is filtered out, fortunately the raw data are still available for analysis, which is the focus here.

Elsewhere there is already published a good deal of data fusion, integration and mathematical and statistical analysis of what multiple datasets can show about buried materials over large landscape-sized areas. Instead my approach is more of a "deconstruction" of complex and voluminous packages of data. This method extracts specific data points (from large magnetic databases) and individual profiles from GPR grids, merges them and uses both to understand what is producing the readings and maps. Then information from that analysis is used to inform what is producing features visible in the larger data set. This method therefore begins with a basic analysis of each method and smaller scale "fusion" is done by directly comparing data along profiles. An imperfect analogy, but perhaps an apt one, is to compare this type of inquiry to that done in deconstructive literary analysis where studying an author's overall significance is approached first by studying individual words, phrases and small parts in a few books. Only then can that knowledge be used to gain a better understanding of a writer's goals and themes.

Case studies presented here using this method are broken into a few basic categories:

1. Substantial architecture (in this case Roman in age) that has in most cases been robbed of stone, with only foundations remaining from Croatia and England. These buried buildings, and other associated features, are in limestone and chalk areas, where the bedrock has little or no magnetic susceptibility or remnant magnetism other than through anthropogenic burning events. The contrasts in magnetic properties are therefore mostly a function of human activity, concentrated organic matter, and some high temperature events. The GPR in these two study areas show significant reflection contrasts between buried architectural features built using mostly non-magnetic stone and the surrounding matrix.

2. A variety of Medieval-age houses and other built features from western Ireland where the bedrock is non-magnetic limestone, and the walls and some other architecture are built of similarly non-magnetic stone. Burned features including floors and extramural architecture are very difficult to image in both GPR maps and reflection profiles, but when those are incorporated with magnetic analysis, they become interpretable.
3. A built environment at a historic site in Connecticut, USA. In this area the bedrock sediment is complex, with some layers consisting of magnetic sediments, and others less so. The near-surface is also very busy magnetically with a good deal of iron objects. There is little in the magnetic dataset that immediately stands out as cultural in origin. The human activity visible in the GPR images shows a number of cellars, wells and surface artifact scatters on a buried living surface. Those architectural features were constructed by both colonialists in the 17th century and native people who might have been contemporaries with the European settlers. When magnetic data are extracted and compared with the GPR profiles, individual geological units' origins and compositions can be determined, and much information derived about the associated cultural features.
4. A prehistoric site in Colorado where hunter-gatherer people lived near a small creek for over 4,000 years, leaving many artifacts, hearths and baking ovens across a landscape that often changed. The GPR profiles show strata within which the artifacts and features are found and the magnetic maps are good at locating burned areas within the strata defined using GPR.

1.5 Some Initial Thoughts on Analysis of Geophysical Data

Elsewhere I have discussed my personal aversion to the use of the word "anomaly" in geophysical interpretation (Conyers 2012). Most of the literature cited above on data fusion and multiple data set interpretation involved a spatial analysis of what are described as anomalies that are discovered either visually or by the use of GIS or statistical algorithms from data plotted or analyzed in map-view. I continue to use the word anomaly in this book liberally especially with regard to magnetic analysis. For GPR I prefer to discuss radar reflection features by their possible origin, or at the very least, some more meaningful description than just "anomaly". Perhaps in the future with more study we can all develop a meaningful way to describe magnetic differences in other ways that are more meaningful than just anomalies. Until that time, I will probably continue to "hedge my bets" on magnetic interpretation and call many of these magnetic features anomalies, as has been historically the case by most researchers.

My intellectual problem with the word anomaly when used geophysically is that it means anything that deviates from a standard, which is sometimes a statistical mean or what is "expected" (Conyers 2012: 29). In geophysics, maps created from raw data of any sort are numerical values, all of which have a mean value (for a profile perhaps, or a map as a whole) and therefore all gridded and displayed values, some of which may have cultural or geological significance, are "anomalies". For this reason all visible features in map form are anomalies, no matter what their origin. In GPR analysis all reflections recorded by antennas are "anomalies", where without differences in the ground that can reflect radar waves to the surface, there would be no recorded reflections whatever. Reflection profiles are by definition displaying high (or perhaps low or even no) relative amplitudes that deviate from a mean. Every reflection profile therefore is nothing more than a map of "anomalous" readings. When all radar reflections are re-sampled and amplitudes from many profiles in a grid are plotted in slice-maps, new anomalies are created that are the spatial placement of new reflection features. Any interpreter who then looks at "anomaly" maps might get lucky and a visual representation of something interesting in the ground could be visible. Often this is not the case, as how those anomalies in a map were actually produced is not understood (Conyers 2012), and maps become an array of high and low values that are given arbitrary colors or shades of gray.

With magnetic mapping the final product is also termed an anomaly map. There are dipole anomalies with positive and negative readings, areas of only positive readings, some areas of negative readings, and often many variations in between, all of which are "anomalous". This becomes even more problematic when using anomalies of unknown origin and applying data fusion models to analyze and compare them, adding or subtracting values to study various correlations, looking for patterns that might be important buried features. When the final product of various analyses of anomalies is interpreted visually to search for these patterns, even with user-supplied "rules" on what is or is not important, the complexity can quickly overwhelm the real data. Resulting "predictions" derived from this type of analysis can still be beneficial if calibrated with what is known about the ground from excavations (Kvamme et al. 2006), however the number of false positives and negatives could potentially outweigh the features of real interest.

1.6 Example of the Method Used to Analyze Both GPR and Magnetics

As an example of the different approach discussed here two basic sediment packages were studied in one grid. In this 20×30 m area both magnetic and GPR data were collected and processed into the standard maps used for most basic interpretation (Fig. 1.2). The magnetic map displays patterns showing some interesting linear anomalies where the positive values are prominent (colored in black) with adjacent less-visible negative readings roughly parallel (Fig. 1.2). The sinuous pattern of these anomalies (mostly the positive readings shown in black) suggests a channel of some sort.

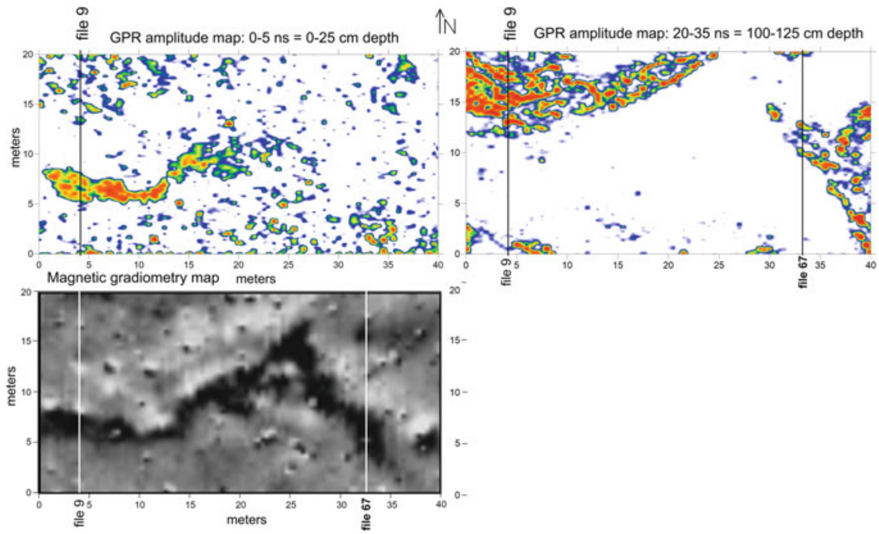

Fig. 1.2 Comparison of GPR amplitude maps and a magnetic anomaly map, Hollister Site, Connecticut, USA

This grid of data was collected on an uplifted late Pleistocene-age river terrace along the eastern bank of the Connecticut River in the eastern USA. A basic geological analysis of the area obtained from the literature (Stone et al. 2005) as well as excavation information nearby shows that this area's surficial geology contains glacial till deposits categorized into various landforms consisting of moraines, eskers and drumlins. These were deposited at the end of the last ice age as the glacial ice had stagnated and was in the process of melting, with the glacial front receding to the north. Those glacial till units are overlain by fluvial sediments, meltwater lake units and in some areas delta deposits, all of which were deposited after the glacial ice had retreated to the north. These sedimentary beds filled in the lower topographic areas between the raised glacial landforms.

The river channel interpretation based on patterns visible in the magnetic map is therefore a good working hypothesis for the origin of these magnetic features. However, the GPR amplitude maps of the same grid appear to be showing other buried units not visible with magnetics while generally showing the same linear features but offset some distance from those visible with magnetics. For instance in the 0–25 cm GPR depth slice (Fig. 1.2) there is a high amplitude linear pattern that occurs in approximately the same location as the high positive magnetic feature that is so prominent. Visually analyzing the 100–125 cm GPR amplitude slice shows a very different feature in the north portion of the grid, which appears to correspond to the area of negative magnetic readings. By only analyzing these images in map form it is clear that a shallow unit is producing the positive magnetic readings and a deeper layer the negative. But the geological reason for this can't be understood by only visually comparing these results in map view.

In order to better understand what units in the ground are creating these various anomalies in both sets of maps, many GPR reflection profiles were constructed and magnetic values were plotted along those same profiles so that the radar information could be directly compared to the magnetic (Fig. 1.3). While the GPR data are always collected in profiles, the magnetic readings displayed here were obtained by selecting the gridded and interpolated values directly from the constructed maps, which correspond to each GPR profile. Those magnetic values were then plotted in profile so that positive and negative values could be directly related to the stratigraphic units visible with GPR. As an example of two composite profiles Fig. 1.3 has colored the significant positive magnetic values red and the negative values blue, only for ease of visual interpretation. The GPR reflection profiles are annotated to show the major stratigraphic units, which also show up nicely in the amplitude slice maps (Fig. 1.2).

In this grid there are three basic layers visible in all GPR reflection profiles, which vary in thickness within upper 2 m (Fig. 1.3). Knowing the basic geology in this area, these units are interpreted as a lower glacial till unit, whose upper surface undulates just as most landforms created as moraines and other fluvial-glacial deposits do when formed during a period of retreating ice. The lower elevations were later filled with fluvial sediments, consistent with a glacial outwash river sediments deposited after the glaciers had retreated to the north. The glacial till in this area consists of sediments derived from far to the north in the Canadian Shield composed of gravel, sand and cobbles consistent with that iron-rich bedrock mineralogy. This gives the prominent till units a high remnant magnetism, which is clearly visible with the high magnetic readings along the profile (Fig. 1.3). Those areas of high magnetism can be seen in the GPR reflection profile where the till is located within about 2 m of the ground surface. Where the till unit is buried deeper than about 2 m, magnetic minerals in the till sediments are below the region of the magnetometer's sensitivity and therefore are not significantly affecting the readings. In the areas where the glacial till was lower in elevation, there are thicker units of post-till river and lake sediments that were deposited between the remnant glacial landforms. Those units contain locally-derived sand and silt that is lower in magnetic minerals, and therefore have a negative magnetic signature (Fig. 1.3). In this example it is important to note that overall this ground has generally high magnetic readings, but magnetic values collected with a gradiometric magnetometer are always measuring variations in magnetism, and therefore displaying positive and negative values from a mean. The magnetic maps are therefore displaying only relative values of magnetism and by comparing them to the GPR-identified units, an interpretation of the magnetic map can be made. This was only possible after magnetic readings were compared directly to the GPR reflection profiles, where two very different sediment units with different magnetic signatures could be differentiated.

In this area the two sediment units discussed are covered with a thin layer of sand and silt deposited during flood events over the last few centuries and capped by a well-developed surface soil. Those more recently deposited units effectively level the ground surface and cover all previously deposited sediments, giving this

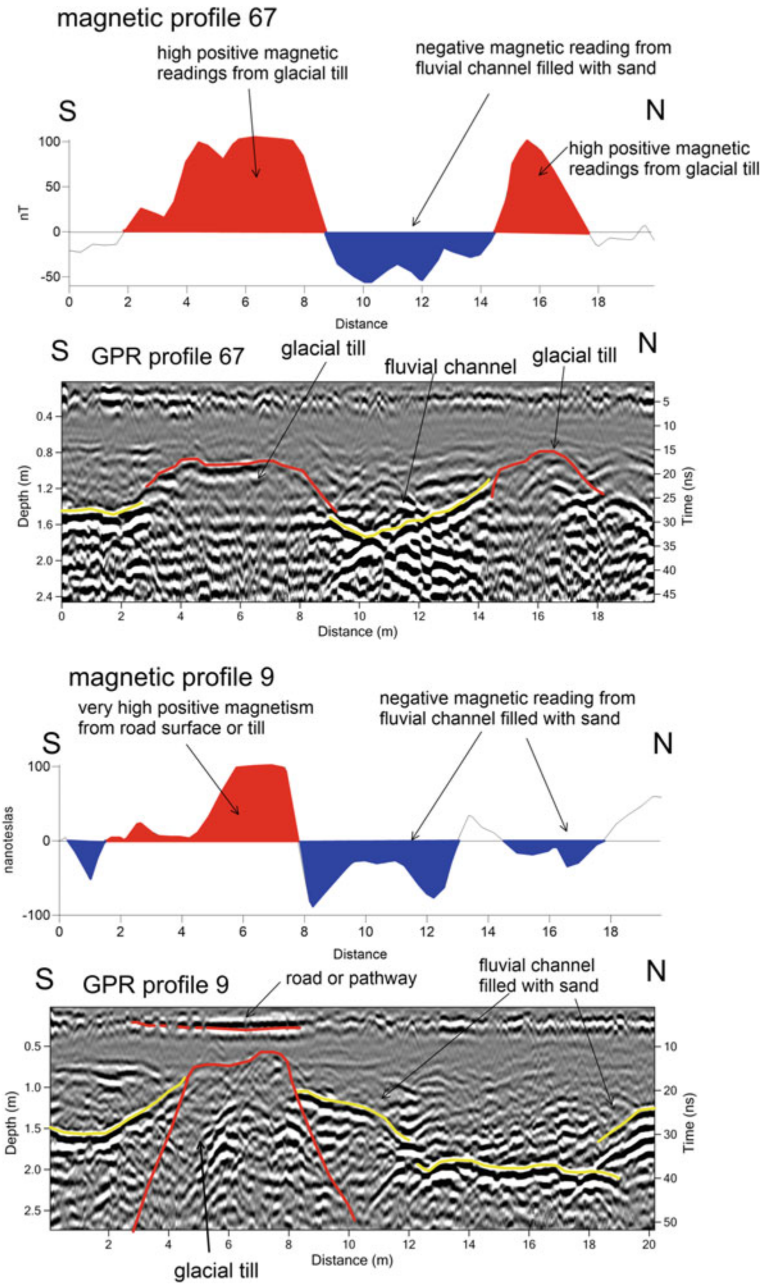

Fig. 1.3 GPR reflection profiles displaying some geological units and the corresponding magnetic readings associated with those units. From the Hollister Site, Connecticut, USA, location of profiles is in Fig. 1.2

ground little if any topographic variation today. There is also no surface evidence of any buried archaeological remains, which were discovered just to the north of this grid, which will be discussed in Chap. 6.

One importance of analyzing these two grids of different geophysical data is the recognition that the GPR slice maps from two levels in the ground are displaying very different sediment units depending on the depths the slices were constructed. The shallower GPR slice-map shows some high amplitude reflections at the top of the glacial till unit (0–25 cm slice in Fig. 1.2) that is visible in the magnetic map as a linear positive feature. The fluvial channel that filled in the low areas between raised till deposits is a negative magnetic linear feature and it is visible in the deeper 100–125 cm GPR slice (Fig. 1.2). The magnetic map, which is a two-dimensional representation of what is in the ground within the top 2 m or so, is therefore displaying features of two very different sedimentary units, each with a different genesis. This is only apparent after interpreting the GPR reflection profiles.

An analysis of this near-surface sedimentary geology and an understanding of the buried landscape in this area is important because other archaeological features discovered nearby are associated to these features, which will be discussed in Chap. 6. This area of Connecticut was first inhabited by native peoples who hunted and gathered along the edges of lakes and rivers. Later they practiced agriculture on the rich soils developed on this raised fluvial terrace surface. In the mid-17th century the earliest European colonialists who arrived in North America founded farmsteads in this same area, occupying a very different area on the landscape where the agricultural soils were richest. When the settlements of these two groups, both with very different adaptations to the historic environment, are placed on this historic landscape that was mapped using geophysics, an understanding of how these different people used and modified their environment can be made. This is crucial to an understanding of the dissimilar human settlement patterns on a buried landscape that can help in determining how these different people interacted (or didn't) in this historically consequential area of New England.

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Chapter 2
Ground-penetrating Radar

Abstract Ground-penetrating radar is a near-surface geophysical method that reflects radar waves from buried interfaces in the ground and produces two and three-dimensional images of buried geological and anthropogenic units. When many thousands or hundreds of thousands of reflections are displayed in two-dimensional vertical slices, profiles of these units can be made and interpreted much like viewing layers in the wall of a trench. When many hundreds of profiles are collected within a grid of closely spaced two-dimensional slices, horizontal maps of the reflective units as defined by the amplitude of the waves produced can be constructed. Those amplitude maps can show geological changes over broad areas such as where certain soils or strata are found, and also the human-produced features on and within those units. An interpretation of what is producing amplitude-defined features visible in map form is possible by analyzing the individual two-dimensional reflection profiles and that interpretation can be used to understand broad areas of study.

2.1 Introduction to Ground-penetrating Radar

Ground-penetrating radar is an active method, transmitting radar waves into the ground, and then recording waves that are received back at the surface. The variables that are measured in this method are elapsed time between sending and receiving a wave, amplitude of the recorded waves, and also data about the frequencies of the waves that are recorded (Conyers 2013). Waves are generated in the ground at interfaces between sediment layers, soils or other features. When many thousands of these wave arrivals are recorded along two-dimensional transects (or in some new methods three-dimensional arrays) accurate depths of visible features and stratigraphy can be produced. The geometry of visualized units, and to some extent the types of materials that have generated reflections in the ground can also be determined. The power of the integrative method of GPR and magnetic information comes by allowing the magnetics to help inform and understand more about aspects of the units visible in three-dimensions with GPR and vice versa (Fig. 2.1).

L. B. Conyers, *Ground-penetrating Radar and Magnetometry for Buried Landscape Analysis*, SpringerBriefs in Geography,
https://doi.org/10.1007/978-3-319-70890-4_2

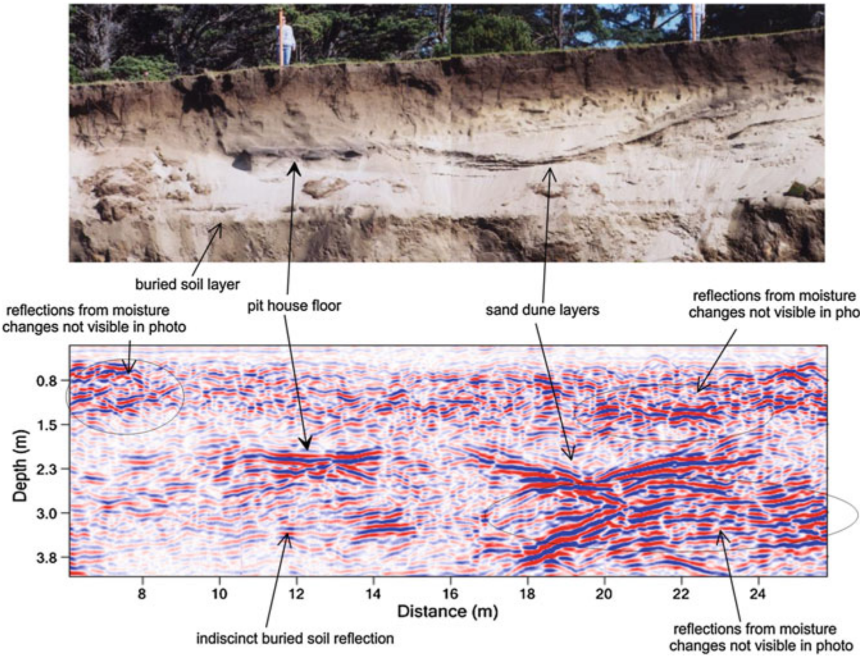

Fig. 2.1 Comparison of units visible in an outcrop with radar reflections seen in profile, along a sea cliff in coastal Oregon, USA

The GPR method transmits radar (electromagnetic waves) energy into the ground and then measures the elapsed time and amplitude of reflected waves as they are received back at the ground surface (Fig. 2.1). Many thousands or hundreds of thousands of reflected waves are collected along the transects of antennas as they are moved along the ground surface to produce reflection profiles of buried layers and features analogous to viewing profiles in excavation trenches (Fig. 2.1). When many reflection profiles are collected in a grid, three-dimensional images of buried materials in the ground can be constructed (Conyers 2013: 166). Ground-penetrating radar therefore has the unique ability to not just produce images of both geological and archaeological units in the ground, but to do so in three-dimensions (Conyers 2012: 20).

Ground-penetrating radar's ability to produce two and three-dimensional images of soils and sediments within depths that are usually of importance for archaeology (a few centimeters to 3-4 meters burial at most) means that complex images of geological materials associated with archaeological deposits is possible. While some archaeological thinking views the geological matrix of a site as a volume of material that must be removed and discarded to get to the important artifacts and features of interest, most recognize that there is important information to be gained by studying these matrix units (Davidson and Shackley 1976; Waters 1992: 15). It was this appreciation that geology and stratigraphy can't be divorced from archaeological research and therefore an analysis of ancient landscapes and environments that gives GPR great utility (Conyers 2016). This cross-disciplinary focus between GPR, magnetics, excavations and an understanding of the geology gives the methods discussed here an ability to study buried and other wise invisible ancient landscapes.

2.2 The GPR Method

Ground-penetrating radar data are acquired by reflecting pulses of radar energy produced from a surface antenna (Fig. 2.2), which generates waves of various wavelengths that propagate downward. They spread as they move into the ground in a cone-shaped geometry that is a function of the physical and chemical properties of the materials through which they pass (Conyers 2013: 47). As these waves move through the ground they are reflected from buried objects, archaeological features and stratigraphic bedding surfaces. The reflected waves then return to the ground surface to be detected and recorded at a receiving antenna, which is paired with the transmitting antenna. The two-way travel times of the waves moving through the ground are measured at the receiving antenna and their arrivals recorded in elapsed time of travel, measured in nanoseconds (ns). As the propagating radar waves pass through various materials in the ground their velocity will also change, depending on the physical and chemical properties of the material through which they are traveling (Conyers 2013: 107). If the constituent differences at interfaces of materials occur abruptly the radar waves' propagating velocity will also change when they pass across the contacts. When this occurs a reflected wave is generated that can move back to the ground surface from the reflection interface. Not all radar waves will travel back to the ground surface at a reflection interface and some energy will continue to propagate deeper in the ground to be reflected again from more deeply buried interfaces, until all the energy finally dissipates with depth. Only the reflected energy that travels back to the surface antenna is recorded and visible for interpretation as some is lost as it moves away from the antennas after reflection.

Reflections generated from radar waves propagating in the ground are created at interfaces where differing composition of materials are in contact along a boundary, and are different enough so that the velocity of moving waves that intersect the interface changes abruptly (Conyers 2013: 27). An example of a composition change that affects velocity in this way might be where a clay unit is overlain by a sand bed (Fig. 2.3). Some other possible scenarios that may or may not generate reflections are also shown in Fig. 2.3. The amplitude of the received waves back at the surface is directly proportional to the change in the speed of the radar waves as they intersect the buried interface, with the greater the velocity change, the larger the reflected wave amplitude. Each abrupt velocity change in a complexly layered area will theoretically create a reflected wave (Conyers 2013: 28). In contrast a gradational change in materials over some distance where there is no abrupt velocity change would not produce a reflection. Velocity changes are almost wholly

Fig. 2.2 A GSSI SIR-3000 GPR system with a 400 MHz antenna and survey wheel

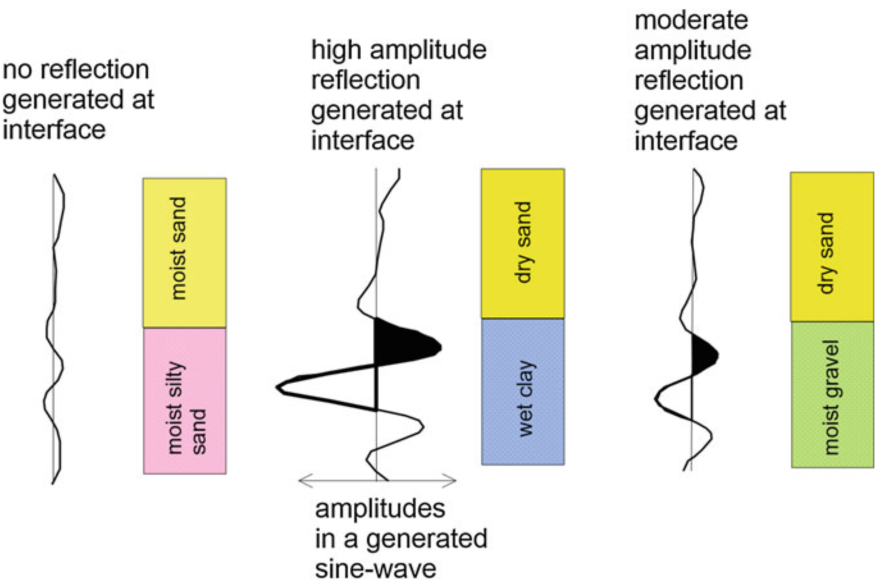

Fig. 2.3 Comparison of reflected radar wave amplitudes depending on the differences in materials along a contact

a function of the amount of retained water in the different buried materials (Conyers 2012: 36). The more interstitial water, the slower the waves will move. For instance wet clay has a very high percentage of water, and will greatly slow radar waves. Dry sand or silt will allow radar wave transmission at a very high velocity. An interface between these two very different velocity units would create a very high amplitude radar wave reflection.

Reflection profiles are the basic interpretive tool for GPR and are created as radar antennas move along the ground surface transmitting waves downward into the ground. A sequential stacking of many hundreds of reflections (termed traces) consisting of reflected waves from different depths in the ground is then produced (Fig. 2.4). Each trace is recorded at a discrete position along an antenna transect, and the display of all these sequentially is used to produce a two-dimensional vertical slice in the ground (Fig. 2.5). Profiles of reflections are the standard images used for many complex stratigraphic interpretations of buried materials in the ground, which is often employed for ancient landscape analysis. These will be used throughout this book, as they can be used to identify and understand geological layers as well as archaeological components within those geological packages. When that information can be studied with the aid of magnetic information that is helpful in determining composition, a great deal can be learned about buried materials in the ground.

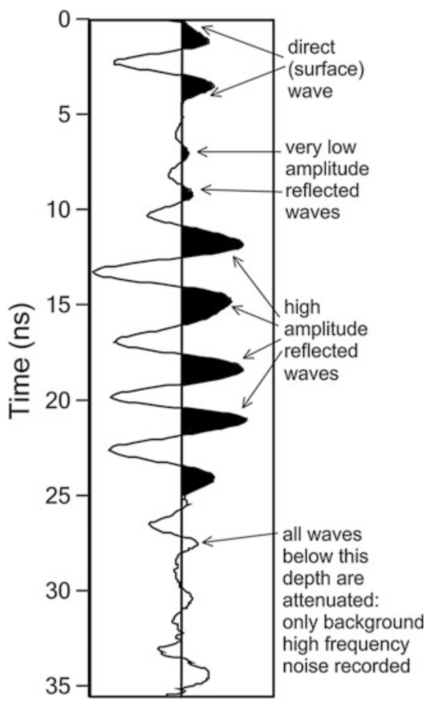

Fig. 2.4 One GPR trace showing amplitudes and attenuation over the time-window

Many reflection profiles collected in a grid can also be processed together in order to produce individual maps of various depth slices in the ground (Fig. 2.5). Often this is quite beneficial in visualizing large areas of ground, and has become the basic image used by many for GPR interpretation (Conyers 2012, 2013). In this amplitude slice-map method all two-dimensional reflection profiles are re-sampled within user-defined depths, and the relative amplitudes of reflected waves located at those depths are then plotted, interpolated and gridded to produce a defined number of horizontal slices in the ground. These are often the images used by many in data

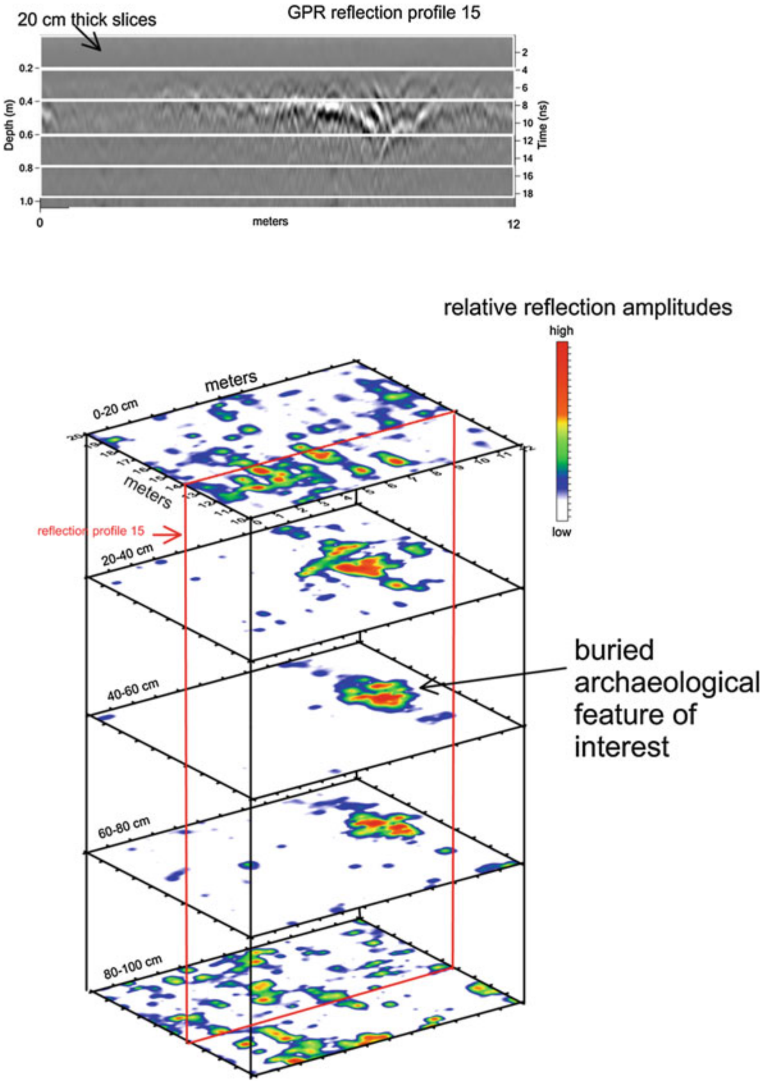

Fig. 2.5 The production of GPR images from collected traces, which are stacked together to produce reflection profiles, and then re-sampled to create amplitude slice-maps with depth

fusion analyses, where depth-slices are directly compared to maps generated from other geophysical methods. The method outlined in this book is to evaluate the individual profiles from which the maps were created first in order to understand what is creating the mapped features in each slice (Conyers 2016). Then once the genesis of all the reflections in the maps are understood, a more complete merging of maps from different depths in the ground can be used in an interpretation.

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Chapter 3
Magnetometry

Abstract Magnetometry is a near-surface geophysical method that measures small changes in the earth's magnetic field, which are a product of differences in the retained magnetism of materials within the upper few meters of the ground. Objects made of iron, or any other highly magnetic material will produce distinct readings of positive (and sometimes positive and negative dipole) readings when plotted in maps. More subtle buried units such as ditches or other features that accumulated organic material over time will be displayed as low value positive anomalies. Built features or disturbed units that are composed of materials lower in magnetic susceptibility than the surrounding ground will be displayed as negative magnetic anomalies. This method can be used to quickly map the extent of these buried features over large areas of otherwise invisible past landscapes, but have little ability to map the depth of those materials. When magnetic readings can be extracted from a broad aerial data coverage, and then compared to the GPR reflection profiles, the units visible with GPR can be interpreted with respect to their composition, at least regarding their magnetic properties. When an understanding of the magnetic properties of buried materials can be understood in this way, the origin of features visible in magnetic maps can be more accurately interpreted.

3.1 Basics of Magnetometry

Magnetometry is a passive geophysical method that uses the earth's magnetic field as an energy source. It relies on the magnetism that is generated deep within the earth where currents within the liquid core generate a magnetic field (Kvamme 2006). This is termed the "main magnetic field", which measures about 50,000 nanoteslas (nT) at mid-latitudes varying from about 30,000 at the magnetic equator to 60,000 at the poles. The main magnetic field (Fig. 3.1) has two poles, the positive (north) and negative (south), which vary in orientation over time (Reynolds 1997: 119). The magnetometry method relies on the energy provided from this field, and functions by measuring minute changes in its strength due to variations in magnetic properties of near-surface materials. Those measurements, often in units

L. B. Conyers, *Ground-penetrating Radar and Magnetometry for Buried Landscape Analysis*, SpringerBriefs in Geography,
https://doi.org/10.1007/978-3-319-70890-4_3

of only a few tens or sometimes fractions of a nanotesla, are then plotted spatially to create map or profile images of the variations in these buried materials that occur within a few meters of the ground surface (Fig. 3.1).

The magnetic method is typically used to survey large areas quickly and efficiently, as the magnetometer sensors need not be in contact with the ground surface (Fig. 3.2). Magnetometers can pass quickly over obstructions, vegetation and other surface materials, and large areas (on the order of many hectares) can often be surveyed in a day. The magnetic readings are then processed into maps that allow for pattern recognition as a way to visualize buried materials of interest, and show the extent and nature of buried archaeological sites and other important features of buried landscapes (Benech 2007; Mohamed-Ali 2012) (Fig. 3.3). In this way magnetometry is most often undertaken as a prospection method to find, and then map, buried sites over fairly large areas.

The basic interpretive method with magnetics is the identification and understanding how magnetic variations are a product of constituents and contrasts in buried materials (Kvamme 2006), termed "anomalies" (Fig. 3.4). Anomalies visible in maps are then identified, annotated, and interpretations regarding their origins are used as a basis for prospecting in areas where little is known about what lies below

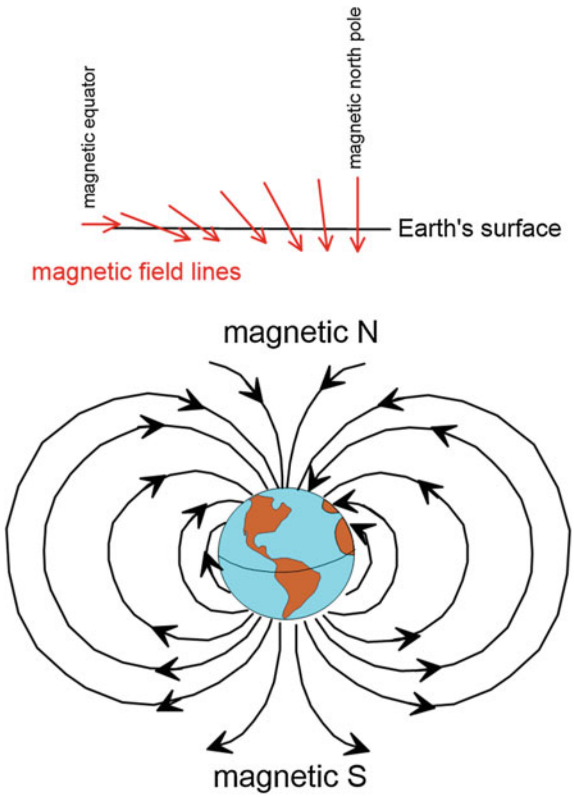

Fig. 3.1 The earth's magnetic field lines of flux in the lower image with a general inclination and direction of field lines for the northern hemisphere in the top image

Fig. 3.2 A Bartington dual sensor magnetic gradiometer system

the surface. In a general sense all magnetic anomalies visible in maps are a representation of differences in materials that vary magnetically as a function of how they modify the earth's magnetic field. While the values collected by magnetometers are measured in units of nanoteslas, those values are really measuring magnetic contrasts between soils, sediments and archaeological materials. In this way it is the *contrasting* magnetic properties of these materials that are important, and while the specific "readings" that are collected can play a role in determining the composition of those materials. For instance, if the soil is highly magnetic, and an archaeological feature within it is composed of materials with magnetic properties that are a little bit less susceptible to the influence of the earth's magnetic field than the surrounding soil, the feature will display negative readings. It will be visible in magnetic anomaly maps by its lower or sometimes negative nanotesla

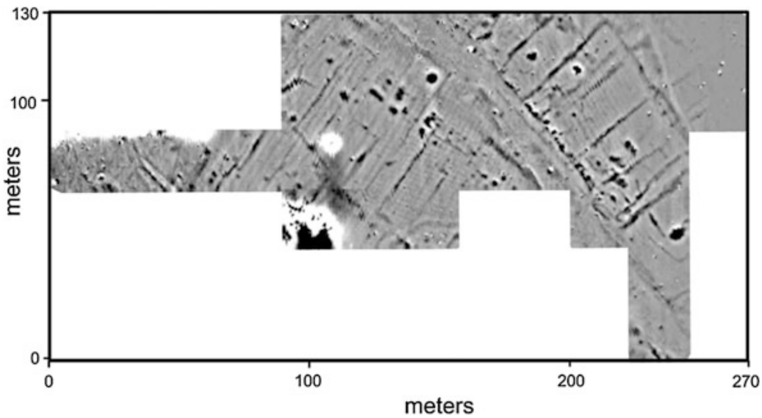

Fig. 3.3 A magnetic anomaly map from western Ireland showing linear field boundaries and distinct round positive anomalies that are hearths and other burned features associated with a buried Medieval farming community

values. The same contrast could occur if the surrounding soil or sediment matrix is only slightly magnetic, and the features of interest within it are just a little bit more magnetic. In this case the anomaly will still appear as a low nanoteslas value, but show a positive contrast with the surrounding material and therefore produce a positive anomaly. This is not the case if the buried feature is composed of iron or has been burned, features which have a very high retained magnetism and those will be displayed as a distinctive and easily recognizable dipolar anomaly (Fig. 3.4).

There are two basic types of magnetism that are measured in buried materials, remnant and induced (Clark 2000: 100). Induced magnetism is the product of a material's magnetic susceptibility, which means these buried units contain some magnetic constituents that are affected by the magnetic field. Remnant magnetism is a property of materials that allows them to retain magnetism as a function of some event that occurred in the past. The most common event that produces remnant magnetism is when an object or material is heated above the Curie point [about 500 °C., varying somewhat with the composition of the materials (Fassbinder 2015)]. These magnetic objects or features retain what is called thermo-remnant magnetism (Burger et al. 2006), oriented with the earth's magnetic field at the time they cooled, and will often show up as a distinctive dipole feature in map view, with a strong paired positive and negative anomaly (Fig. 3.4). There are other less common types of remnant magnetism termed detrital, chemical and even lightning strike-induced (Fassbinder 2015; Reynolds 1997: 129).

Many decades ago researchers noticed in magnetic anomaly maps that buried features, which were not magnetic rocks, iron or features or materials that had been burned, still showed positive magnetic anomalies (Fassbinder et al. 1990). These were shown to be buried materials that had a higher than background magnetic susceptibility due to the presence of magnetite and maghemite minerals (Clark 2000: 100). Even small concentrations of these minerals in the ground can create

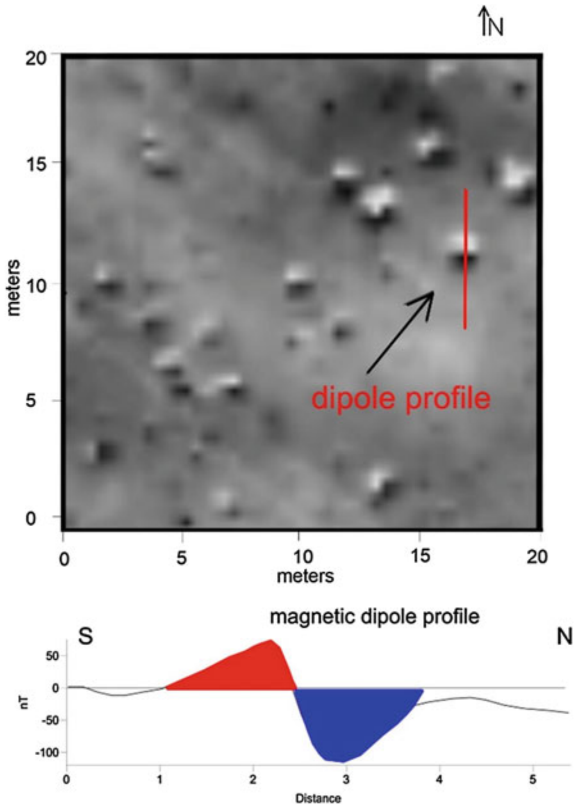

Fig. 3.4 Magnetic map showing many dipole anomalies produced by near-surface iron artifacts. In profile the larger ones display the distinctive positive and negative paired-readings are displayed, with negative to the north

variations in the earth's magnetic field and be visible in maps, if the magnetometer making the readings has enough sensitivity (Reynolds 1997: 120).

An analysis of the magnetic susceptibility of materials is therefore important in understanding those properties and therefore the genesis of features that magnetometers are measuring in the ground. Rocks that are high in magnetic minerals such as basalts and other basic-composition rock types have retained magnetism and therefore have a very high magnetic susceptibility (Fig. 3.5). Other igneous rocks such as granite, and many metamorphic rocks are usually somewhat lower in susceptibility and vary depending on the amount of iron-mineral constituents. Limestone and dolomite have a very low magnetic susceptibility with chalk even lower. Soils can vary in magnetic susceptibility as a function of the parent material they were formed on and within (Birkeland 1984) and also by the amount of iron minerals that have been precipitated and formed in them by physical and biological processes over time.

Soils often contain iron minerals that make them magnetically susceptible due to precipitation of iron by pedogenic processes and also by the biological concentration by bacteria of some iron minerals (Fassbinder et al. 1990, Fassbinder 2015).

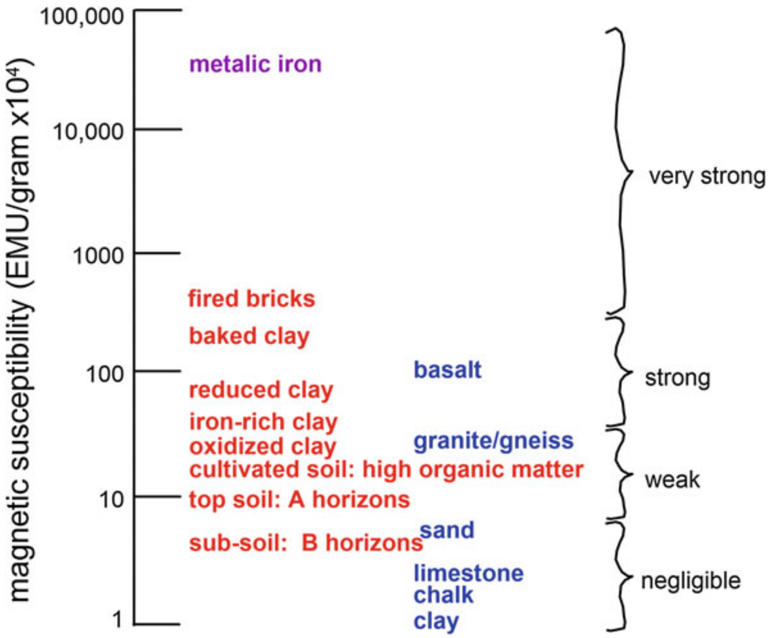

Fig. 3.5 Some magnetic susceptibilities of common rocks, soils, artifacts and features

Natural variations in the oxidation and reduction of iron minerals in the soil will also allow the transmutation of hematite, which is non-magnetic, to maghemite, which is. This transformation can be enhanced when the decomposition of organic materials occurs by bacterial action (Aitken 1958). While these chemical processes are still not completely understood (Fassbinder 2015), it is well known for the purposes of magnetometry (Aspinall et al. 2009) that organic-rich soils or sediments will often have a higher magnetic susceptibility than surrounding ground. There are a number of variables that appear to affect these magnetic mineral variations in soils such as temperature, climate and weather, all of which affect the chemical pathways of iron minerals (Fassbinder 2015).

An analysis of the spatial extent and patterns of magnetic variations in maps can be used as interpretive tools for understanding buried materials. Positive values could indicate areas with iron-enriched soils that have a relatively higher magnetic susceptibility to the earth's magnetic field than surrounding areas. In contrast, if there were a sand-filled channel composed of lower magnetic susceptibility sediment that is surrounded by a more iron-rich soil, the channel will be displayed as a negative magnetic anomaly (Kvamme 2006). Ditches filled with organic material can often have a higher magnetic susceptibility than the surrounding soil because of biological action and will appear as a positive anomaly, if the surrounding ground is lower in magnetic susceptibility.

Areas where there were fires, iron artifacts, magnetic mineral-rich stones, or bedrock unit with magnetic minerals often appear as distinct dipoles with paired positive and negative anomalies (Fig. 3.4). Depending on their size, depth of burial, orientation and location in magnetic latitude these anomalies can take on a variety of shapes and sizes. The complexity that occurs where many dipoles occur in one area because of the presence of multiple magnetic materials can create a wide array of anomaly shapes and sizes (Burks and Cook 2011; Cook et al. 2015).

Limestone foundations or walls of buildings will often be lower in magnetic susceptibility than the surrounding matrix, and will show up as negative contrast areas (Fassbinder 2015). The same is true with sandy channels and cellars filled with flood sediment (Fig. 3.6). Soils often contain many materials with somewhat similar magnetic orientations created by iron-rich minerals that were precipitated, chemically altered or by bacterially produced mechanisms over time (Fassbinder 2015). If those soils were excavated and then used to re-fill the hole (as in a grave) these magnetic orientations will then become "randomized" and may appear as a negative contrast in magnetic maps. Other less common changes in the orientation of minute amounts of iron minerals in sediment and soil occur with the dissolution of these minerals due to ground water leaching (Fassbinder 2015) or changes in the level of the water table in localized areas producing sometimes produce negative readings. Preferentially retained water in the ground in different areas will also produce lateral changes in magnetic readings across a survey area, and make an interpretation of the values visible in maps more difficult.

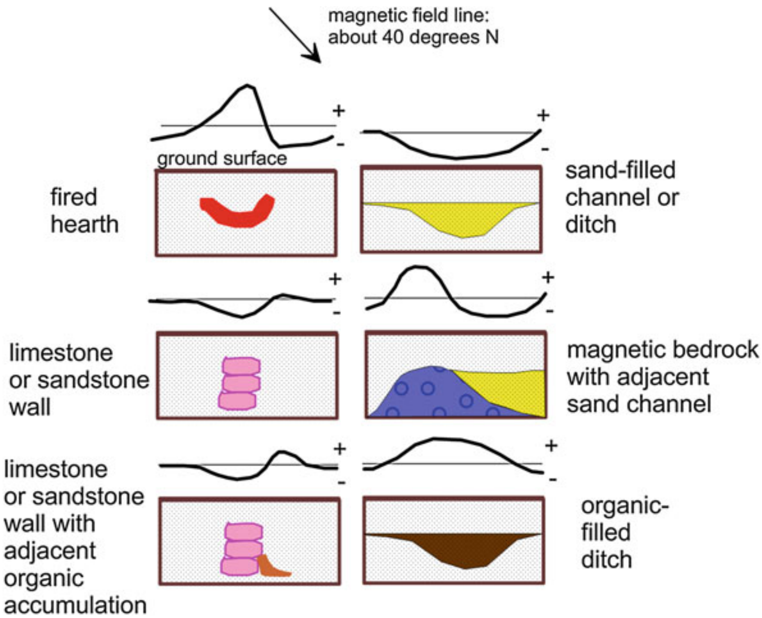

Fig. 3.6 Some magnetic anomalies produced by buried geological and archaeological features, simulated at about 40° north magnetic latitude

A direct connection between a magnetic anomaly visible in a produced map, and specifics about what is in the ground producing that anomaly are not always clear or interpretable (Fassbinder 2015). While the overall spatial "pattern recognition" can often yield an accurate interpretation, there are a number of other factors about the ground that affect the visual anomalies that are often less clear. This is where integration with GPR can be very useful, as GPR maps and profiles produce very accurate three-dimensional images of individual units in the ground irrespective of their magnetism. When the magnetism of the units in a study area is understood in the context of the types of features visible with GPR, a much more complete understanding of the extent and composition of materials in the ground can be produced.

3.2 Magnetometer Systems Typically Employed

Magnetometers were invented for military applications in the 1940s and soon after were experimented with in archaeological contexts (Alldred 1964; Aitken 1958; Weymoth 1986). The first magnetometer regularly used for near-surface archaeological or geological applications was the proton precession system, which was used to measure the both total magnetic field of the earth (Kvamme 2006) and also could be used in gradiometer mode. When these early magnetometers were used for total magnetic field collection diurnal changes that were measured at a nearby base station were used to adjust the acquired data (Aitken 1958).

While some of these magnetometer systems are still used, most work is done with fluxgate and alkali vapor (cesium) systems (Fig. 3.7) in gradiometer mode. Gradiometers employ paired magnetic sensors separated some distance vertically with both simultaneously measuring the earth's magnetic field along transects. The differences between the two readings are then used to produce maps and profiles. The concept of a gradiometer is that changes in the external magnetic field cause by diurnal magnetic field variations have little contribution to the differences caused by the presence of buried materials in the ground (Witten 2006: 88). By subtracting the readings from the upper and lower sensors, the external or distant magnetic field contribution is essentially eliminated and even very weak magnetic variations produced by near-surface magnetic materials can be detectable. Magnetic gradiometry relies on the understanding that magnetic fields from sources far away are essentially identical at both upper and lower sensors. The remnant differences in the measured magnetic field are therefore almost wholly a function of differences in magnetic susceptibility or remnant magnetism in the ground. When measuring with a gradiometer, the contributions of magnetism from deeper materials in the ground is also suppressed, and as a result usually only the upper 1.5–2 m of ground is being analyzed (Witten 2006: 108). More deeply buried materials can possibly still be located and mapped if the measurements from just one sensor (which are always saved digitally in all systems) are used from gradiometer collection, which is equivalent to a total field analysis.

Fig. 3.7 Cesium gradiometer with two sensors, supported by a homemade carrying device constructed by Helmut Becker for ease of packing and traveling

Prior to collection gradiometer magnetometers are first “zeroed” or normalized for the ground to be surveyed in an area that is hopefully either an area with average magnetism or the system is raised far enough off the ground so that the magnetic field in that location can be “zeroed out” with minimal influence from materials in the ground. Magnetic readings are then collected sequentially along transects within grids, with a programmed number of readings made per meter (or readings are collected with a certain number of readings per unit time, which are then placed into space during data processing). In gradiometer mode as data points are collected along transects the readings from the upper sensor are subtracted from those in the lower sensor, and all data are saved digitally. If the ground at one location is more magnetically susceptible than at the zeroed location, it will appears as a positive value. Areas with positive readings are therefore showing locations where the earth’s magnetic flux lines (Fig. 3.1) were just a little bit more “concentrated” due to those magnetically susceptible buried materials. Negative readings in an area indicate just the opposite showing the location of buried materials that are relatively less magnetically susceptible than the zeroed-out value where the magnetometer was first normalized prior to conducting the survey.

Gradiometer readings are collected in values of nanoteslas (nT), and usually the upper reading is subtracted from the lower reading and then plotted. In this way the upper reading is indicating the earth’s magnetic field with less influence by any magnetically susceptible materials in the ground while the lower sensor nearer the ground is more influenced by material in the ground. Subtraction of the two values therefore removes the earth's magnetic field measurement with the residual reading indicating the magnetic susceptibility of near-surface materials (Mussette and Khan 2000: 175).

3.3 Variables that Affect Magnetic Readings

The amount of remnant magnetism and induced magnetism (as measured by the magnetic susceptibility of the material) are the most important variables that affect magnetic readings, with the mapped variations of these readings the goal of most surveys. However, before interpretations can be made other variables must first be taken into account. Below are some of those variables that affect magnetic readings and especially the patterns visible in profiles and maps:

1. The magnetic latitude (distance from the magnetic north and south poles) that will alter the orientation of dipoles, which vary considerably between the poles and the magnetic equator (Fig. 3.1). For instance, a dipole produced from a highly magnetic body in the ground at 30° north from the magnetic equator will look very different than one at the equator or the north or south magnetic pole (Fig. 3.8). These offsets due to latitude become less important when mapping broader changes in the variation in magnetic susceptibility of materials in the ground, but must still be taken into consideration, as there will be spatial "offsets" between the location of features in magnetic maps, and the actual locations of materials in the ground.

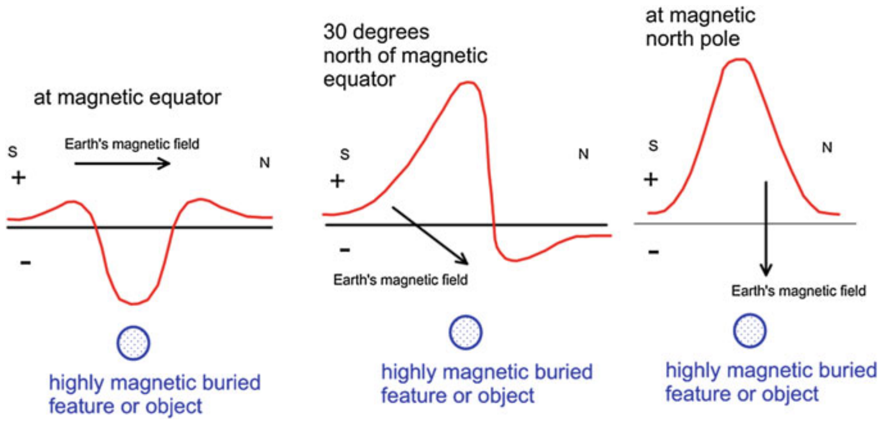

Fig. 3.8 Differences in dipole shapes and readings of a magnetic object at three magnetic latitudes in the northern hemisphere

2. Variations in the size of buried features produces very different measurements, with some smaller objects displaying very low magnetic readings and others that are very small being effectively invisible.
3. Depth of burial is also very important, with buried materials yielding lower values with increasing depth. With most magnetic gradiometers, the effective depth of "detection" is at most about 2 m (Kvamme 2006).
4. The orientation of a highly magnetic feature or object in the ground can produce a very different anomaly in map form (Gaffney and Gater 2003). Orientation coupled with the depth of burial and magnetic susceptibility all taken in unison will vary greatly the shape and intensity of visible anomalies (Kvamme 2006).
5. Background noise, which could be caused by a variety of metal objects on or near the surface will greatly affect magnetic readings. For this reason, magnetic surveys in urban environments are often a failure due to the abundance of nearby iron materials. Noise might also be soil disturbances, which have homogenized the ground such as intense human activity or burrowing by animals. Water that is preferentially retained in some areas could also create background "noise" that affects interpretation by obscuring some features (Fassbinder 2015).
6. Instrument sensitivity can vary a good deal, with total field instruments often capable of greater depth readings than gradiometry (Fassbinder 2015). There can also be changes in instrument readings over a few hours due to temperature variations (Kvamme 2006).
7. The angle and strength of the magnetic field over the face of the earth affects anomaly size and geometry, with very different readings at the magnetic equator than found closer to the poles (Fig. 3.8). Diurnal variations also must be accounted for during collection using the total field method. These are caused by changes in the secondary magnetic field of the earth (as opposed to the primary or main field). This external field is created in the ionosphere by the flow of charged particles from the sun and can vary due to the gravitational attraction of both the sun and moon. These vary by the minute all through the day, and can become intense during solar storms (Burger et al. 2006: 438). For the most part these diurnal variations are negated by collecting with magnetic gradiometers, as only the differences in readings between sensors are used to create the final images. Diurnal effects are rarely more than about 100 nT, but this is more than enough to make subtle differences on the order of 1-2 nT invisible (Mussette and Khan 2000: 167).

3.4 Data Processing, Modeling and Displays

There are a number of ways that readings collected in the field must be corrected prior to creating accurate and usable maps. These involve "de-staggering" of lines and the filtering of data so that all readings within grids are reflecting the same changes in the ground (Kvamme et al. 2006). A variety of quantitative analysis can also be done on the raw data collected that can take into account the modeled geometric forms of the materials in the ground, and their size and depth (Telford et al. 1990; Reynolds 1997:167). Accurate models can be created of the materials in the ground, if desired (Burger et al. 2006: 456; Musette and Khan 2000: 170). In a general sense magnetic anomalies become wider and are measured as lower readings with greater depth.

Collected readings are usually processed in a number of ways so that values obtained from multiple adjoining grids are integrated and edge-matched to normalize mapped values over large surveyed areas (Kvamme. 2006). Prior to interpolating and gridding to display all values in map view, a number of other common errors must be accounted for. There can be "heading errors" and instrument drift that creates offsets and variations in readings along adjacent profiles and also over large areas. A number of commercially available programs will determine and adjust for these errors. Other common adjustments must be done for staggering affects caused during the collection of many profiles within grids that create "herringbone" anomalies. These can easily be adjusted for by calculating the staggering differences and spatially adjusting values all in profiles within grids. Other filtering processes of data have also been applied using a number of statistical evaluations of data prior to mapping (Kvamme et al. 2006).

An example of a magnetic gradiometer map ready for interpretation contains subtle positive and negative magnetic values and a distinctive pattern is visible that appears to be a buried building (Fig. 3.9). In this map the positive readings are colored black and negative white, with gray variations between. A few distinctive dipoles are visible that are likely recent iron objects on the ground surface. The area surveyed is in southern England, and the ground is for the most part very low in magnetism, with a chalk and limestone bedrock.

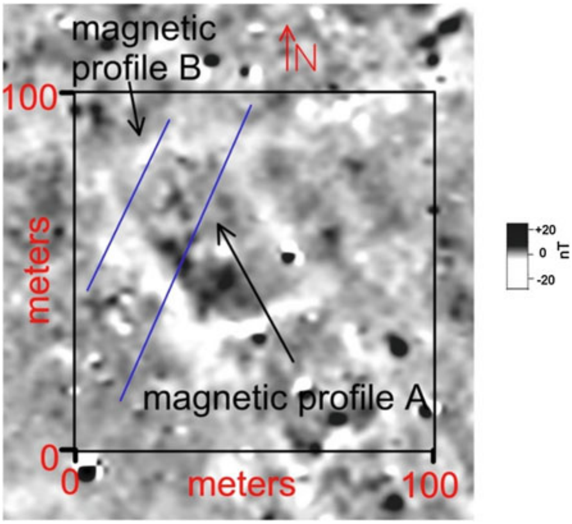

Fig. 3.9 Magnetic gradiometer map showing a large rectangular building that exhibits negative values along what appear to be walls. The profile locations shown are displayed in Fig. 3.10

The most interesting buried feature is the outline of a large building whose walls, or perhaps foundations for what were once walls (Fig. 3.9). Inside those walls are some positive values, but these areas are localized and do not perfectly align with the negative value rectangular walls. Most of the positive magnetic readings are within the walls, and very few outside, other than those associated with small dipole anomalies.

Two magnetic profiles were constructed from the processed and gridded values used to construct the map in Fig. 3.9. The construction of these profiles serves no great interpretive purpose, as it is not known what is causing these magnetic variations without some information from excavations, or GPR profiles that can show actual architectural materials in three-dimensions. Using only the magnetic map the interpretation of a large rectangular building can be made by pattern recognition alone. Some higher magnetic readings within the building may be concentrations of organics, or perhaps partially burned materials that accumulated within the walls (Fig. 3.10).

However, when a number of GPR reflection profiles are compared to magnetic profiles across this building, and others adjoining it, a direct comparison can be made using the two methods (Fig. 3.11). The GPR reflection profile shows that there are buried walls, likely composed of the local limestone, which have been robbed near the surface for building stone sometimes in the past. Those robber trenches are visible in the GPR profiles, and can be seen to have a negative magnetism compared to the other readings in this grid. The trenches used to obtain building stones were likely filled in after these excavation events with the same materials that were dug out. The surface soil's magnetic particles were then "randomized" during this process and appear as negative features in the magnetic map. What is really showing up in the magnetic maps is probably these trenches,

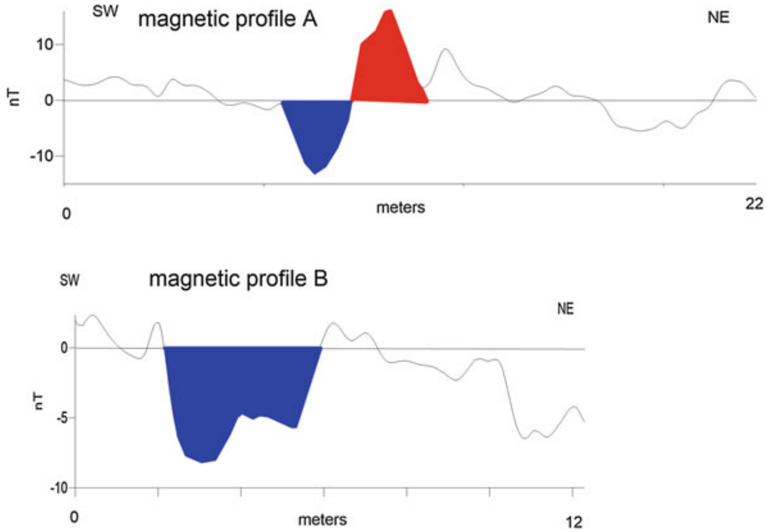

Fig. 3.10 Magnetic profiles, the locations of which are shown in Fig. 3.9, across a buried building

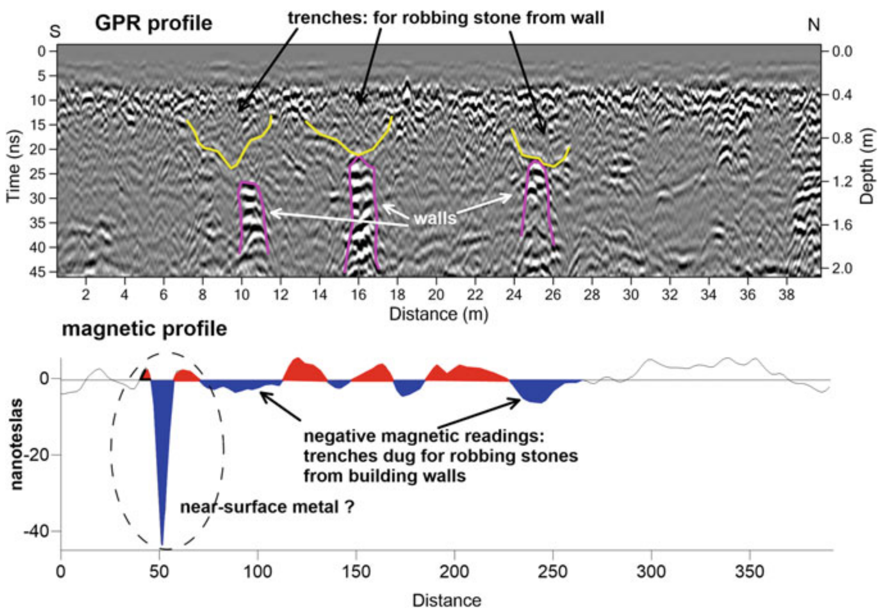

Fig. 3.11 Integration of a GPR profile and magnetic readings showing the walls of the large building visible in Fig. 3.9. The GPR reflections in profile indicate that the negative readings are likely showing the location of robbers trenches used to obtain the building stone, and not the walls

not necessarily the readings from the walls. While the limestone stone walls may be contributing additional negative magnetic readings, their depth of burial makes that contribution somewhat minimal as the wall tops are about 1 m deep. The relatively high magnetic readings that can be seen in this profile between the robber trenches, are probably showing the "natural" relatively higher magnetic readings of the soil that was not excavated.

In this case an interpretation based only on the magnetic map would have accurately shown the location of the building. Only when the magnetic readings were integrated with the GPR reflection profiles could a more accurate analysis of the more subtle features in the ground be made. The interesting negative pattern visible in the magnetic map accurately shows the location of the building, but the GPR image shows much more clearly how it is the trenches above the extant walls that are producing the magnetic anomalies.

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Chapter 4
Small Roman Site in Croatia

Abstract A small Roman building is used as a test case for the merging of ground-penetrating radar and magnetic gradiometry images to help understand what each method is displaying in both profiles and maps. At this site the foundations of the building, composed of weathered limestone, readily appear in magnetic maps as negative magnetic features, and the building's general architecture can be discerned. The GPR amplitude maps only show a few linear features that are highly reflective, and the wall foundations are effectively invisible as they include few stones or vertical walls that reflect radar waves. When each of the individual GPR reflection profiles are viewed in two-dimensions the floors and some wall foundations are visible, and the magnetic readings associated with them show that the horizontal surfaces are composed of materials that are lower in magnetic susceptibility than the surrounding ground (likely clay or lime plaster material). There were holes dug through the floors after the structure was abandoned, filled with slightly magnetic material, which is likely sediment higher in organic matter than the surrounding units. An analysis of the GPR profiles shows that it is the edges of the holes cut through the floors that created the high amplitude reflections seen in the GPR amplitude maps, not the walls or wall foundations. Attached to his building is less substantial architecture interpreted as a courtyard enclosure and possible cooking area where fires were used, as the ground and artifacts found there are higher in magnetism.

4.1 Background to the Site

At a late Roman site in Croatia a small grid of GPR and magnetic data were collected by Fabian Welc and Radoslaw Mieszkowski of University of Warsaw, Poland over a small area where it was thought there might be buried architecture. This grid provides a good small-scale test of the integration of GPR and magnetics and shows how at this site neither of the methods is producing an accurate representation of the buried building that was discovered. Only when both are analyzed

L. B. Conyers, *Ground-penetrating Radar and Magnetometry for Buried Landscape Analysis*, SpringerBriefs in Geography,
https://doi.org/10.1007/978-3-319-70890-4_4

in detail by studying individual profiles and specific anomalies, and then integrating that information in a iterative way, can this small site be interpreted accurately.

4.2 Data Collection and Analysis

The GPR data were collected using a Mala system with the 500 MHz antennas and the magnetic data with a Bartington twin gradiometer. There was no visible surface expression of any architecture in the grid area and only one core hole that yielded some basic information on stratigraphy was available prior to the geophysical study. This area near the Adriatic Sea has a limestone bedrock with surface soils generally low in magnetic susceptibility.

The GPR reflection profiles in this 10×20 m grid were sliced into 4 ns horizontal slices, each of which is approximately 30 cm in thickness (Fig. 4.1). The most interesting reflective features are visible in the 10–14 ns (75–105 cm depth slice), which displays a very distinct rectangular feature of high amplitude reflections, which was initially thought to be a building. However, the magnetic map appears to be indicating a much larger building than was visible in the GPR amplitude slice-maps (Fig. 4.1), and a direct comparison of the two indicated there is very little direct spatial correlation in possible architecture.

The magnetic anomaly map shows a number of wall-like patterns that are visible as negative readings, with some high positive magnetic anomalies in a few locations within these possible walls (Fig. 4.1). Most of the magnetic anomalies in this grid are about ± 10 nanoteslas, and are therefore unlikely to be showing metal or baked features such as hearths, which would display higher readings and likely be visible as dipolar anomalies. The wall-like features in the magnetic map are all negative values, similar to what was seen for the large buildings in England (Fig. 1.1). The most striking thing about these negative-value magnetic "walls" is that they do not coincide in space with what appear to be "walls" in the GPR amplitude map (Fig. 4.1) except in a small area. There is also an interesting broad band of high magnetic readings to the south of the hypothesized building, which have no immediate explanation other than they are unlikely to be architectural.

In order to understand why there was a poor correlation between the GPR and magnetic features in this grid, each GPR profile was analyzed and the main architectural features visible with GPR in profile were plotted (Fig. 4.2) In this analysis GPR point-source reflections and planar reflections were mapped, irrespective of their depth in the ground. The hyperbolic reflections were interpreted to be the tops of walls with the planar reflections likely floors, if they were found within the walls (Fig. 4.2). There were also some sloping high amplitude stratigraphic layers to the south of the building, which may be slope-wash sediments consisting of sediments that were eroded from near the building and deposited down-slope in that direction. The point-source GPR reflections form three linear features making them likely walls (Fig. 4.2). Other reflections of this sort may be

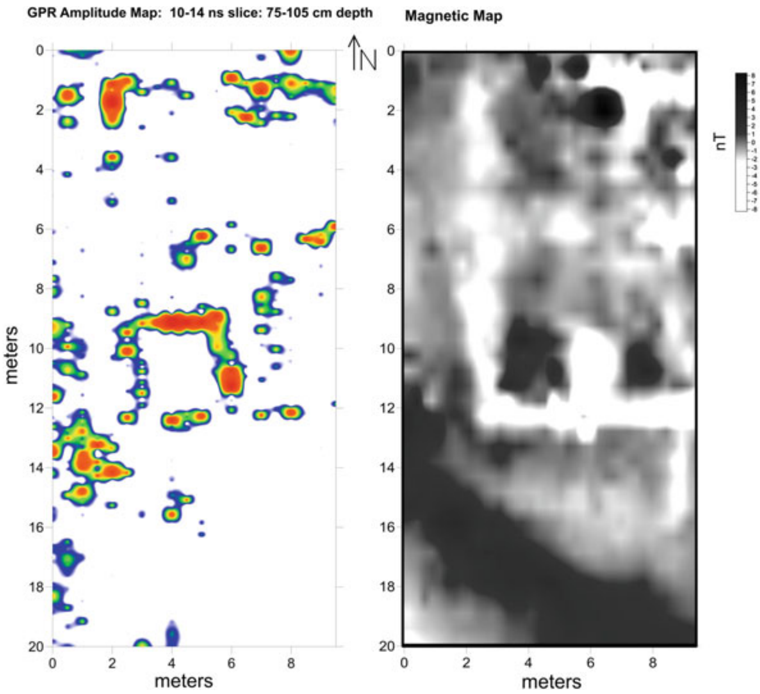
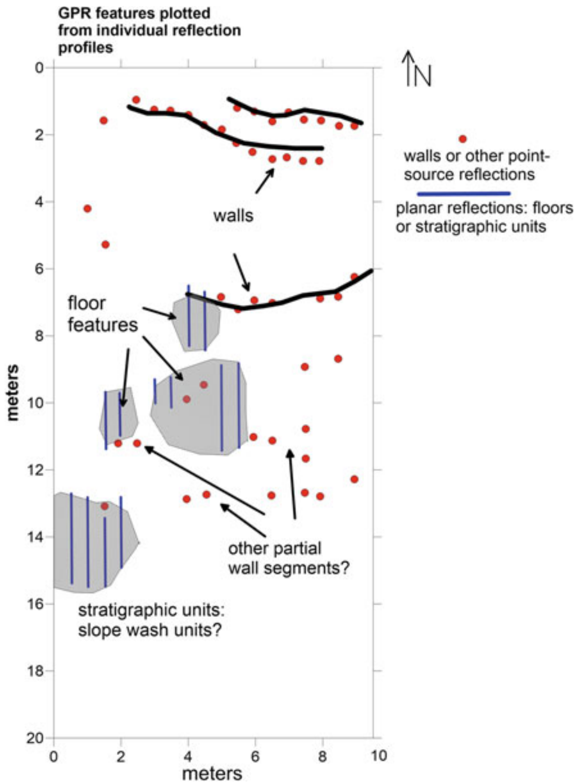


Fig. 4.1 GPR amplitude slice-map showing one "square" feature visible in the middle of the grid, and other possible linear features elsewhere. This depth is approximately 50–80 cm in the ground. The corresponding magnetic map displays a much larger building than is visible with GPR as negative magnetic readings. There is little direct correlation between the two images

partial walls, with the some either robbed of stone or collapsed with their stones no longer present in the subsurface as upright features.

An analysis of the likely floor reflections from GPR profiles indicates most occur between the walls, and that in places the floors are truncated (Fig. 4.3). This suggests that sometime, probably after the building was abandoned, holes were dug through the floors. The walls, consisting of individual stones were likely obtained from nearby limestone quarries and all display distinctive negative magnetic readings (Fig. 4.3). Limestone has only a very weak magnetic susceptibility (Fig. 3.5) and therefore the negative linear features so prominent in the magnetic map are indicating walls, or foundations of walls where the stones have been removed. The floors are neutral or have slightly negative magnetic susceptibility and do not appear in the magnetic map (Fig. 4.1). The holes that were dug through the floors have slightly elevated positive magnetic values, suggesting they were filled in with sediment that contains perhaps more organic matter than surrounding units and these features therefore exhibit an increased magnetic susceptibility and positive values compared to the surrounding material.

Fig. 4.2 The location of the point source and planar reflections interpreted from individual GPR reflection profiles



The broad area of slightly higher magnetic values to the south of the building (Fig. 4.1) may be indicating the location of slope-wash materials that washed downslope from the building. This could be organic-rich refuse that was discarded there when the building was in use, or debris with elevated organic matter that washed in that direction after its abandonment.

The general outline of the walls that are visible using GPR is shown in Fig. 4.3 placed on the magnetic map. Those GPR-identified walls are point-source reflections interpreted from the individual reflection profiles, in most cases not those features visible in the amplitude maps. Amplitude maps constructed from GPR profiles can sometimes be an exceptionally good tool for mapping buildings of this sort when the walls are standing or at least the lower courses of stone are still in place (Conyers 2012: 45). Here it appears from an analysis of individual profiles that only some of the walls are still in place and therefore reflect radar energy in a way that their tops could be identified (Fig. 4.1). In much of the grid the walls, if they still exist at all, are barely visible in GPR profiles and what stones were at one time present have likely been removed. Slicing techniques that produce horizontal maps using all the GPR profiles will only identify the most distinct and highest amplitude reflections from the in-place walls, and therefore provide a very

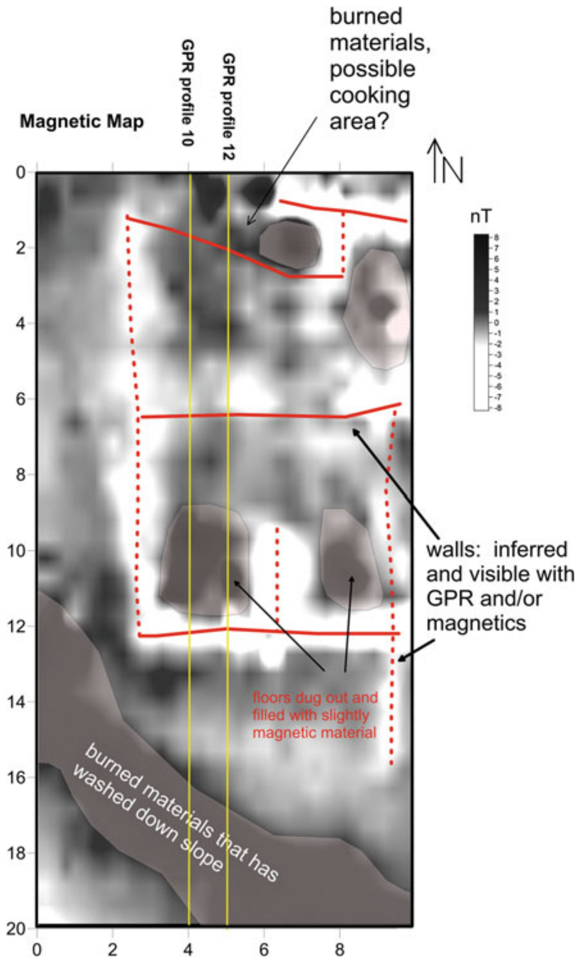


Fig. 4.3 Comparison of GPR analysis obtained from reflection profiles to the magnetic anomalies

incomplete picture of this building as it once stood. The magnetic map is better suited to display the foundations of the walls as negative readings, as these are composed of low magnetic susceptibility material and remain in place.

In order to understand aspects of both the GPR and magnetic datasets that will allow for a more complete understanding of this buried building, each of the GPR reflection profiles was then studied individually. This can be very time consuming for a large grid, but this small area only consists of 21 profiles, so the process was somewhat simplified. For each GPR profile radar travel times were converted to depth. Magnetic values were then taken directly from the gridded and interpolated magnetic map that coincide with each GPR profile, and they were compared visually (Fig. 4.4).

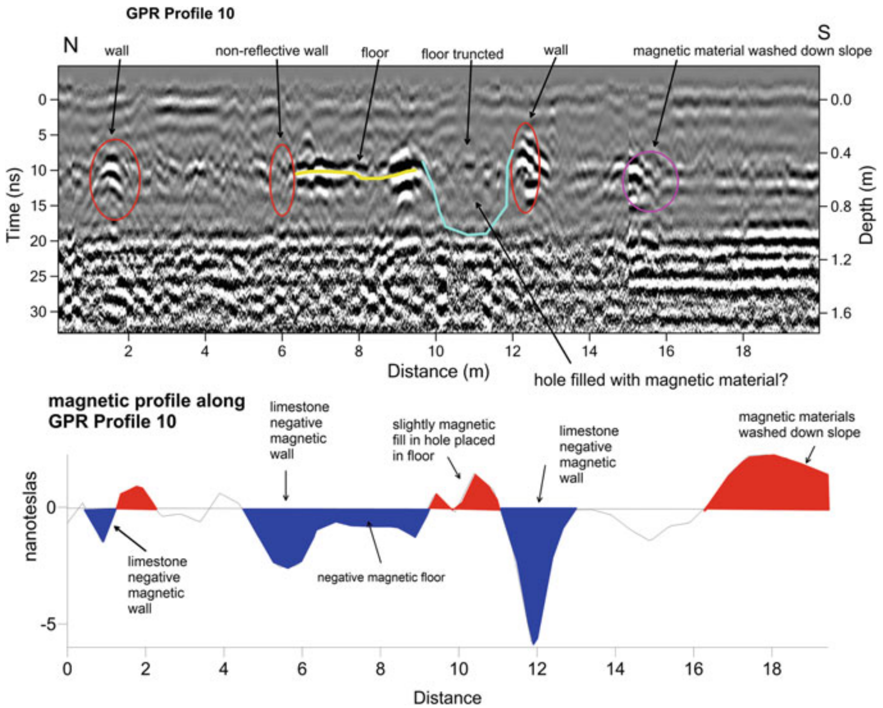


Fig. 4.4 Comparison of GPR reflection profile 10 (location shown in Fig. 4.3) comparing features interpreted in the radar reflections and showing their magnetic signatures to determine their composition

This direct comparison of the two data in profile is instructive as floors and walls can be seen in profile using GPR, and their magnetic readings understood. In this analysis the floors, which are visible in GPR profiles as high amplitude horizontal or sub-horizontal planar reflections always display negative magnetic readings (Fig. 4.4). These floors were likely paved with clay or lime plaster, both of which have a very low magnetic susceptibility. The walls that still have a course or two of stone present and which are therefore visible in GPR profiles also have negative magnetic readings. They are composed of the very low magnetically susceptible limestone derived from the local area. Where the structure's walls have been removed, their foundations still retain enough low susceptible limestone-derived material to show up in the magnetic map (Fig. 4.1) but are not visible with GPR. Two areas within the building's walls where the floors were cut into and distinct holes are visible in the GPR profiles, and were filled with material that is providing slightly positive magnetic readings (Fig. 4.4). It is likely that after the abandonment of this building people removed the structure's walls where the stones were suitable for reuse, and cut into the floors during this process for unknown reasons. The pits were then filled with sediment, which perhaps had an elevated organic content due to standing water and plant growth. These holes are visible as distinct positive magnetic anomalies in the magnetic map (Fig. 4.1) along the southern walls of the structure.

The only areas of this small grid where there are abnormally high positive magnetic readings are associated with the still-intact walls on the northern edge of the grid (Fig. 4.3). That area for some reason was not robbed of stone after abandonment, and at least the lower courses of the wall are still intact. The GPR amplitude map shows some linear walls in that location (Fig. 4.1) and they are visible in the GPR reflection profiles. Associated with those walls are distinct dipolar magnetic anomalies (Figs. 4.4 and 4.6). The GPR profiles only show indistinct walls in that area, but the magnetic readings indicate that associated with those walls were localized areas where burning events produced thermally induced remnant magnetism. One hypothesis that can be derived from this analysis is that the area on the north was used for cooking or other activities of this sort that required fires (Fig. 4.5).

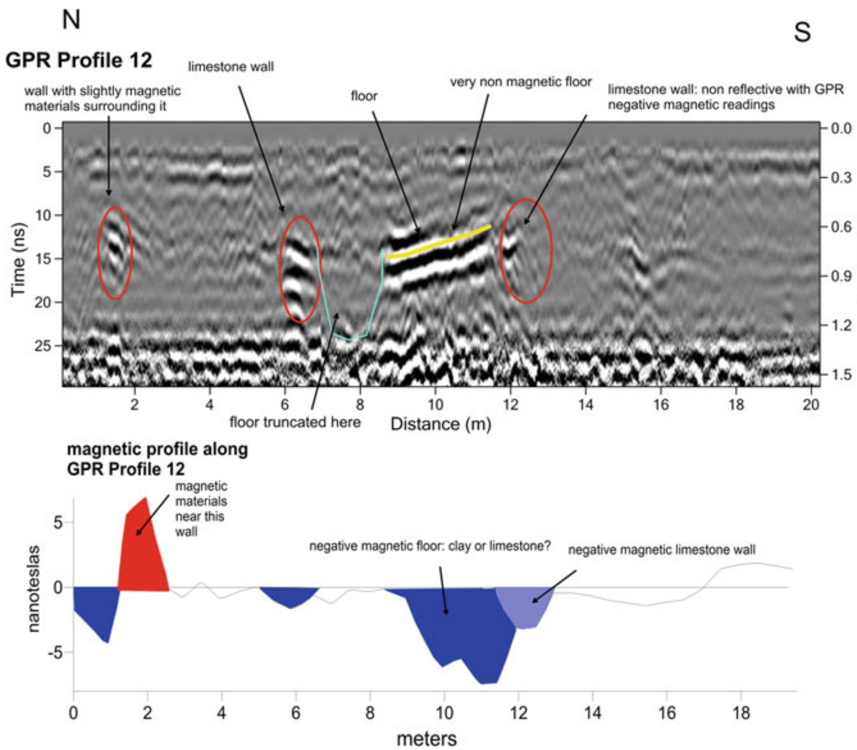


Fig. 4.5 Comparison of GPR reflection profile 12 and the magnetic readings along this same transect. The location of this profile in the grid is shown in Fig. 4.3

4.3 Conclusions

Once the features visible with both GPR and magnetic methods are integrated and the abilities of the two techniques are understood, this small grid can be interpreted with greater clarity. The magnetic map and the anomalies within it are very good at identifying the low magnetic susceptibility walls and their remaining foundations as negative magnetic features. Their limestone composition produces an easily recognizable structure outline. The intact floors of this building are not visible with the magnetic image, but are very distinct in the GPR profiles. The locations where those floors were dug out and the resulting holes were later filled in with sediment are very distinct in the GPR reflection profiles. Those incised floor areas have slightly elevated positive magnetic readings indicating they were filled with material of a slightly higher magnetic susceptibility than the surrounding ground. Those areas of higher positive magnetism can be seen to perfectly fit within the two southern rooms of the building where the floors were cut out and holes created (Fig. 4.6).

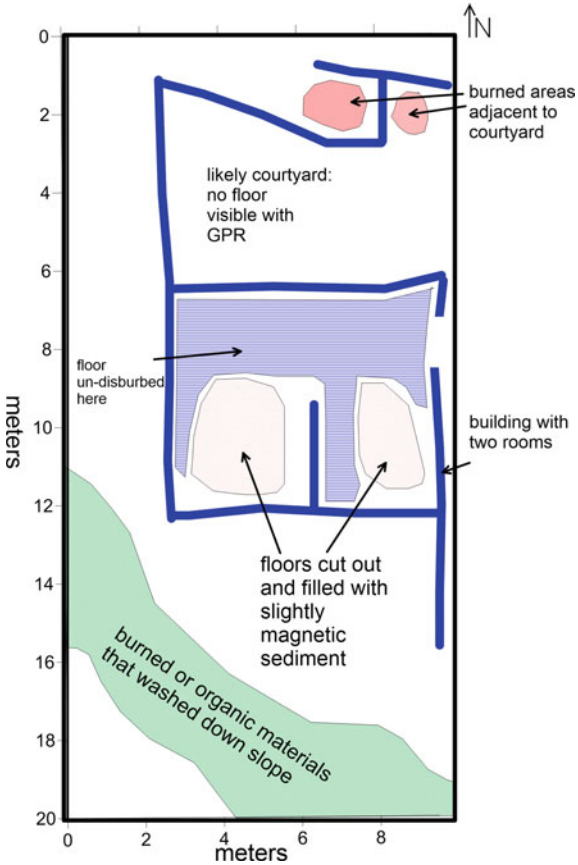


Fig. 4.6 General functions and post-abandonment features of this small structure consisting of two habitation rooms and an attached courtyard with a possible cooking area to the north

Most of the building stone of this structure appear to have been removed, as there are very few distinct linear features in the GPR amplitude map (Fig. 4.1) and the reflection profiles show few distinct point-source reflections especially in the southern two rooms (Fig. 4.2). The foundations for those walls, which was likely limestone rubble or other locally derived material was not salvaged for reuse and still produces a negative magnetic reading allowing the structure to be identified with magnetic mapping.

There is only one area where there appears to be some walls intact, on the northern edge of the grid (Fig. 4.2). This area also displays a few magnetic dipole anomalies, which is suggestive of burning events (or perhaps buried iron objects?). For some reason these walls of the building were not dismantled for stone, perhaps because those individual stones were not considered to be valuable and not worthy of recycling. The dipole magnetic anomalies there suggest fires were used for some activity. The northern area of the structure must have had a more utilitarian function than the southern part.

An overall interpretation of this grid of GPR and magnetic maps and profiles allows for the production of a model for this structure's function during its use and also what happened to it after abandonment. The magnetic map readily shows a two-room building on the south, with a partial wall separating the two rooms. This part of the structure was probably made of well-crafted stones and had a floor constructed from clay, or perhaps paved with lime plaster producing negative magnetic readings. The entrance to this building was to the east, with an attached courtyard just to the north. That open area may have been a work area or perhaps used as a domestic animal enclosure. It has no distinctive floors visible on GPR profiles, unlike the two rooms to the south. There is also no wall visible to the east of this possible courtyard. The attached structure to the north of the open area consists of two walls associated with what were likely cooking or other fire-related activities.

To the south of the building is a broad positive magnetic area that can be seen on GPR profiles to have layered sediments consistent with depositional units (Fig. 4.6). That area appears to contain layered sediment, which produces a broad area of positive magnetism (Fig. 4.1). It may be a more elevated organic-rich deposit that could have been where refuse was disposed of during the building's occupation. That area is equally likely to have been where some remains of the building were re-deposited after it was abandoned.

The two distinct southern rooms were likely the living quarters of this building that were disturbed after abandonment and the floor was cut out by digging. The stones that made up the walls of this building were also removed at this time.

Once the specifics of the two methods were understood a much more complete analysis of this small grid was possible. The GPR amplitude map was misleading as it only showed one distinctive square feature (Fig. 4.1). The high amplitude reflections that produce this square feature are not the wall foundations but instead were produced from the edge of the hole that was dug through the floor and had the appearance of a squared-wall structure. Without the magnetic map that is denoting the structure's foundations of low magnetic susceptibility material, the outline of the building would not be visible.

This could have been the home of someone with enough means to have constructed two rooms with stones valuable enough to have been recycled after it fell out of use. Its floors were well paved and where they are still partially intact and show up in GPR profiles as distinctive planar reflections. The occupants utilized a courtyard to the north, attached to a more simple structure where burning occurred. Refuse was probably discarded all around this building, but is visible geophysically as a high magnetic susceptibility apron to the south of the main two room house.

It appears that most of the more well-constructed portion of the house was dismantled after it was abandoned, leaving only foundations and a few scattered wall stones. Two holes were then cut through the floors of the southern two rooms for unknown but potentially interesting reasons.

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Chapter 5
Roman Temple in England

Abstract A buried Roman temple in England was readily mapped using GPR amplitude slice-maps, but was difficult to identify with magnetic mapping. An integration of the two methods shows that the temple and its surrounding precinct has distinct walls, which produce radar reflections. Those walls are not composed of stones that are magnetic, and are slightly less magnetic than the surrounding ground. Areas where the stones had been robbed in trenches, and then those trenches were backfilled with soil and sediment, appear as negative magnetic anomalies. Two very highly magnetic areas north and south of the temple complex were places where burned materials were placed in excavated holes in the ground. In one of those holes distinct horizontal surfaces are visible with GPR adjacent to the holes, which may be the floors of buildings that stood there prior to the temple construction, and which were burned and pushed into the hole. A small post-Roman period building that was likely constructed of wood within what were still standing walls of the temple was effectively invisible in the magnetic maps, and very difficult to see in GPR maps. The GPR reflection profiles across this small building show that it was filled with sediment, and contains a possible hearth, visible with magnetic readings.

5.1 Background to the Site

Analysis of a grid containing substantial architecture is the next step in the interpretation of ancient cultural landscapes using both GPR and magnetic geophysical methods. An 80 × 80 m grid of geophysical data were collected at the small Roman town of Durobrivae (Water Newton) in northern Cambridgeshire England by Kris Lockyear (University College London) and his students and colleagues. This site contains the remains of what was a small Roman town known for its commercial pottery industry with some villas nearby (Fincham 2004). The architectural stone is locally-derived sandstone and the bedrock geology is mostly low magnetic susceptibility material with surficial sand, gravel and silt of fluvial origin. Good building stone is difficult to obtain in the local area, and while there were

L. B. Conyers, *Ground-penetrating Radar and Magnetometry for Buried Landscape Analysis*, SpringerBriefs in Geography,
https://doi.org/10.1007/978-3-319-70890-4_5

possible quarries nearby where the local sandstone was obtained in the past, much was also recycled from older buildings.

The site was excavated from 1820–1827 and again in the 1950s (Perrin 1999). Local people often noted standing walls in one small area to the west of the walled town called the "fort". Those walls are no longer standing, perhaps having been robbed for building stone in the last few decades. There has been some discussion in the literature about this so-called fort as a military installation, as it sits in a defensive location. Prior to this geophysical work it was only vaguely visible in aerial photos and no excavations have been conducted here. The 1950s excavations also uncovered Roman-age kilns for ceramic production south and southeast of the town (Perrin 1999).

It was hypothesized that there might be some other interesting Roman structures in this area, as there are linear and circular crop marks in aerial photos. The study area is about 250 m west of the main part of the Roman city, which consists of strip buildings along roads, domestic structures, one central temple, and a number of workshops (Burnham and Wachter 1990: 81). This Roman city was known for its pottery production, and a good deal of kiln, ceramic workshop debris and clay dumps have been discovered in excavations. Metal and leatherworking were also conducted in what was no doubt a thriving Roman industrial center.

5.2 Data Collection and Analysis

Two grids of GPR were collected and then merged into one large grid using the Mala GPR system with 500 MHz antennas (Fig. 5.1). Reflection data were sliced in 6 ns horizontal slices, each of which is approximately 30 cm in thickness. The slice from 120–150 cm in the ground shows much of the architectural pattern from Roman and perhaps pre-Roman buildings. The shallower slices also show this general architectural pattern, but these radar maps are mostly showing random stones that had been scattered about over the centuries.

By pattern recognition alone the GPR amplitude map shows two major areas of architecture, one of which is likely a central temple (the *cella*) where images or statues of gods were kept and offerings were received. This square building is surrounded by a walled ambulatory making up the remainder of the sacred precinct (De la Bédoyère 2002). The other significant buildings visible in the GPR maps are rectangular strip buildings along what are likely roads to the northeast (Fig. 5.1).

Overall this grid is quite "busy" as it is cluttered with many radar reflections, some of which are linear features and therefore likely walls, many of which could have archaeological significance. Two areas were chosen for detailed analysis, one within the presumed temple complex, and one just to the north (detailed areas #1 and #2 in Fig. 5.1). The large buildings on the eastern portion of the grid were discussed earlier (Fig. 1.1) as they exhibit very good examples of negative magnetic anomalies associated with post-Roman trenches that were used to obtain their building stones.

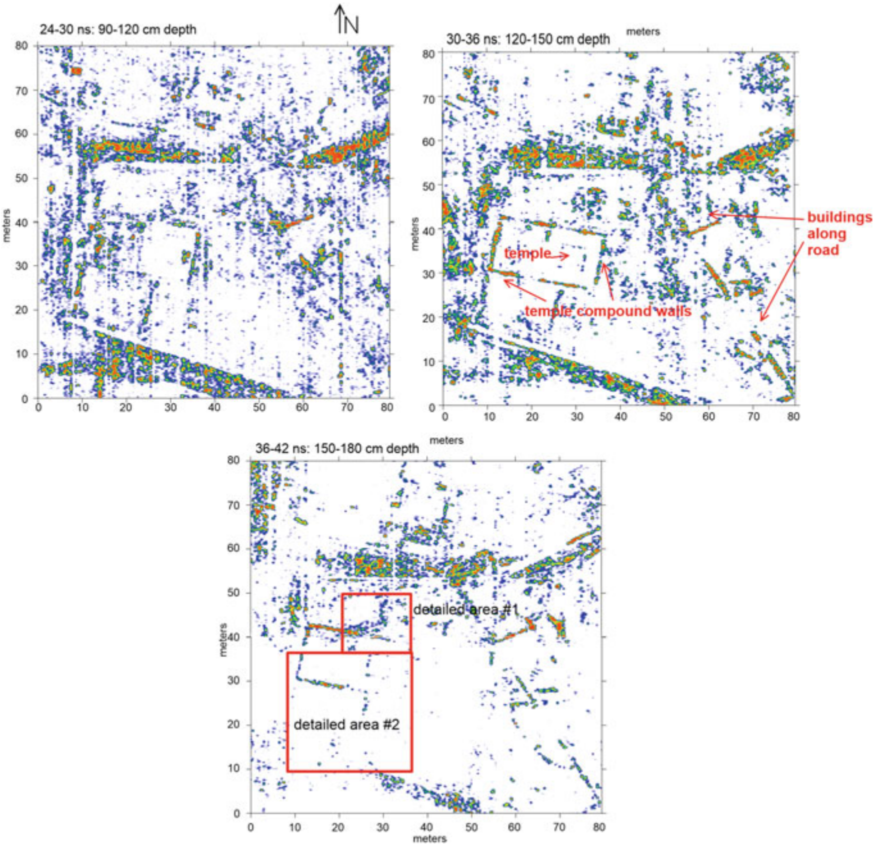

Fig. 5.1 Three GPR amplitude slice-maps containing high amplitude reflections displaying prominent architecture of a likely temple complex consisting of a central *cella*, and a surrounding ambulatory. Three strip buildings are visible along a road to the east

The magnetic map, constructed from data collected using the Foerster Quad gradiometer, covers the same grid as the GPR (Fig. 5.2). A cursory pattern analysis of the anomalies shows the walls of the large buildings on the east as negative linear magnetic readings, and correlate well with the GPR map that reveals these same walls. Elsewhere two very high magnetism areas are prominent and many clusters of high and low magnetic anomalies scattered throughout the map. The distinct temple walls that are so visible in the GPR map are not visible without a great deal of imagination in the magnetic map.

The detail area #1 encompasses a very strong positive magnetic anomaly that has values of many hundreds of nanoteslas over a large area (Fig. 5.2). From this anomaly's extent and high readings alone this area appears to have experienced one or more burning events that created material with a high remnant thermal magnetism.

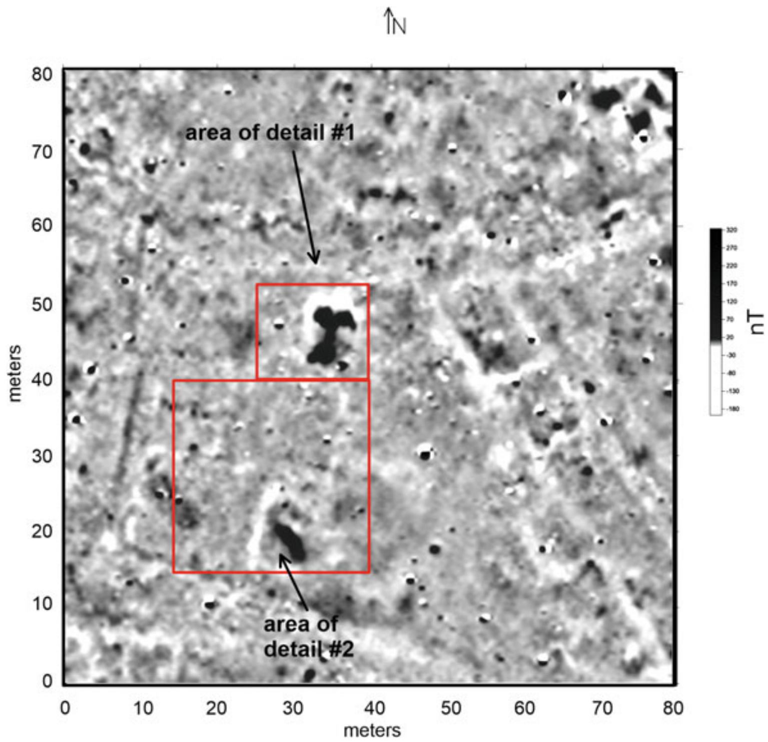

Fig. 5.2 Magnetic map showing a number of both positive and negative linear features, with the detailed area grids #1 and #2 outlined

A high resolution GPR amplitude map was constructed over the detailed area #1, and profiles were re-sampled and gridded to produce maps with pixels created every 5 cm for maximum definition of features (Fig. 5.3). These detailed amplitude maps show that there is a concentration of individual radar reflective features in the middle of the very high magnetic region on the southern edge of the feature. To the north there appears to be a more aerially extensive "surface" with a rounded north edge visible in the amplitude map. This horizontal surface probably consists of a concentration of individual objects as there are individual reflections from the large rocks along this reflection surface (Fig. 5.3). One area of high magnetism corresponds well to the area where there are concentrated radar reflections and the extensive planar surface.

All GPR reflection profiles were then analyzed in this small grid, and magnetic values were extracted that correspond to each profile. Profile 71 (Fig. 5.4) is representative of the GPR reflection profiles and corresponding magnetic values across this feature. It shows a distinct hole in the ground that was about 80–100 cm deep. It is filled with a number of sediment layers, suggesting that its filling did not occur during one event, but over time as various different materials were put or

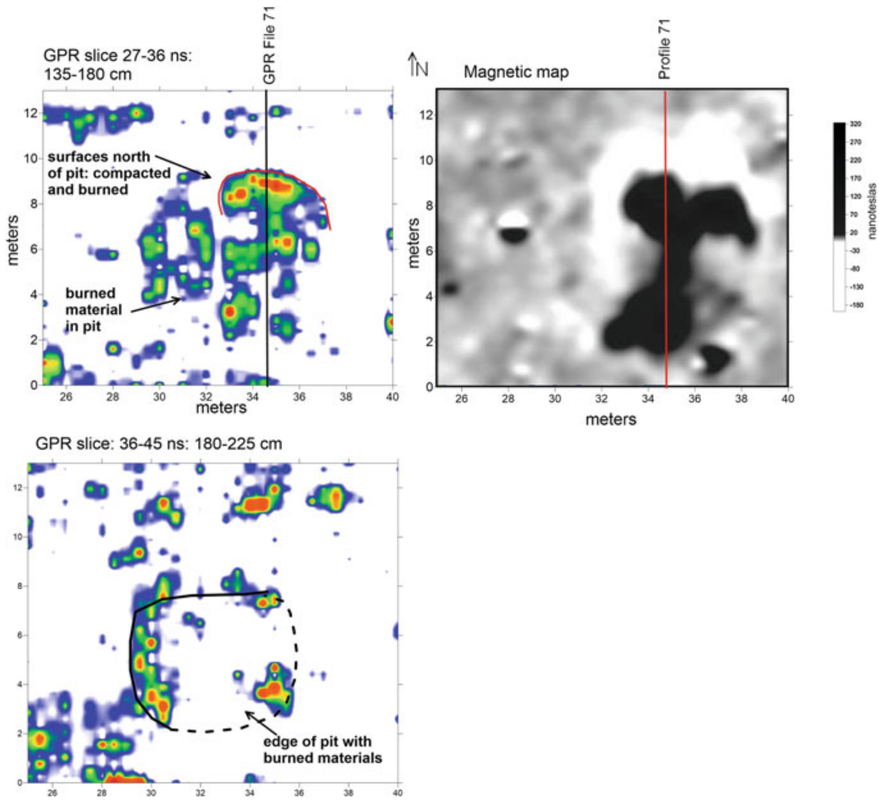

Fig. 5.3 GPR and magnetic maps for detailed area #1 used as a base for the detailed analysis of profiles. Location of this grid is shown in Fig. 5.2

washed into the hole, each of which reflects radar energy along the interfaces between units.

The magnetic values associated with the hole are very high and all are positive, showing that it was filled in with burned material, or was filled with combustible material and then that material was burned (Fig. 5.4). Distinct high amplitude GPR planar surfaces project to the north from the hole, and also exhibit very high positive magnetic readings. The origin of those layers is not immediately known, but it is possible that they are surfaces on which fires were burned, and then perhaps the remains of those fires were shoveled into the nearby hole.

Other likely scenarios exist for this interesting feature. Kris Lockyear suggests that this, and a similar large burned area to the south (to be discussed below), were areas where the burned remains of offerings from the nearby temple were discarded and covered over. Many temple complexes in Roman Britain had subsidiary temples outside the main complex with altars where sacrifices and offerings took place (De la Bédoyère 2002: 243). Perhaps this feature is related to one of those

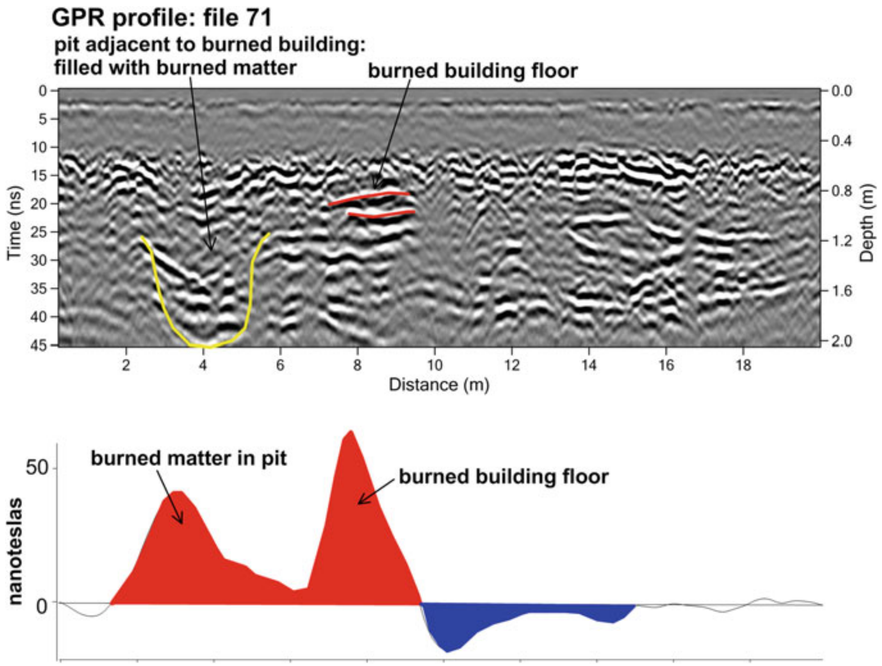

Fig. 5.4 GPR reflection profile 71 within the detailed area grid #1 (location in Fig. 5.3). A hole is filled with highly magnetic materials, bounded on the north by some stacked planar surfaces that are highly magnetic

structures. Another hypothesis is that this burned area is the remains of a late Iron Age house that was removed prior to construction of the temple. Iron Age houses were usually circular with pole and wattle construction (Cunliff 2004: 270). The northern edge of the floor of this feature is rounded (Fig. 5.3) and the GPR reflection profile indicated two burned surfaces, which could be floors of this building. Perhaps this house was burned and its remains put into the nearby hole and covered over. The burned surfaces to the north of the hole, visible with the GPR profiles, could be the remaining floors of that house that were not destroyed. Remains here were then covered over and the land was left open near the temple.

The second area of detailed analysis is to the south of the temple and its surrounding open space, which contains another very high magnetic anomaly (Fig. 5.2). The same method was used, with magnetic readings used in conjunction with GPR profile analysis as a way to understand materials in the ground (Fig. 5.5).

In profile 54 (Fig. 5.6) another hole is visible in profile much like that to the north. It perfectly correlates with the high magnetic values. This hole was also about 80–100 cm deep (like the one to the north) and is filled with many small objects, each of which produces a small radar reflection. The highest positive magnetic readings correspond to the bottom of the hole, and the magnetism is less intense toward its margin. Perhaps a burning event took place soon after this hole

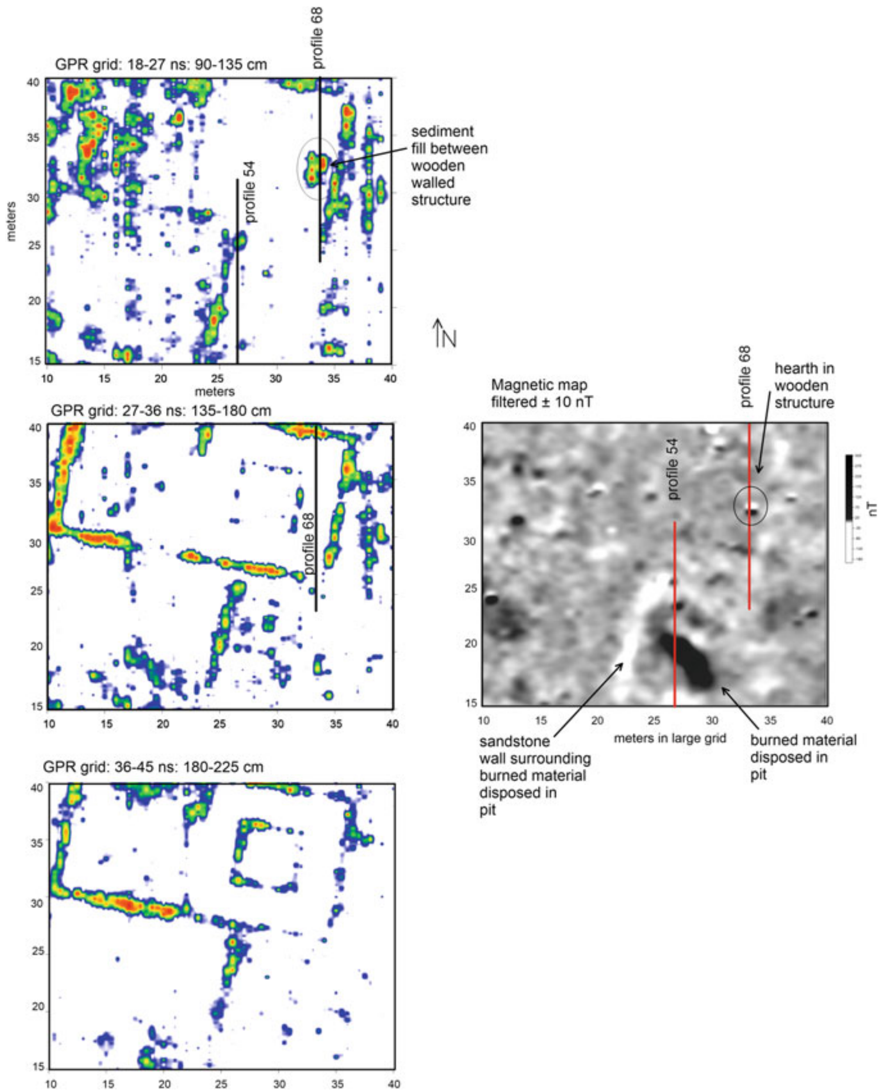

Fig. 5.5 GPR amplitude maps and the magnetic map of detailed area #2, location of which is shown in Figs. 5.1 and 5.2

was dug, and the most intense heat was at the bottom of this large pit. It was filled with many objects, just like the hole to the north of the temple.

If these holes both north and south of the temple were used for the disposal of burned offerings from the temple, then there may have been a good number of these over time, and perhaps as a hole in one area quickly filled up with this material and a new one had to be constructed. Or using a different hypothesis, if these holes were

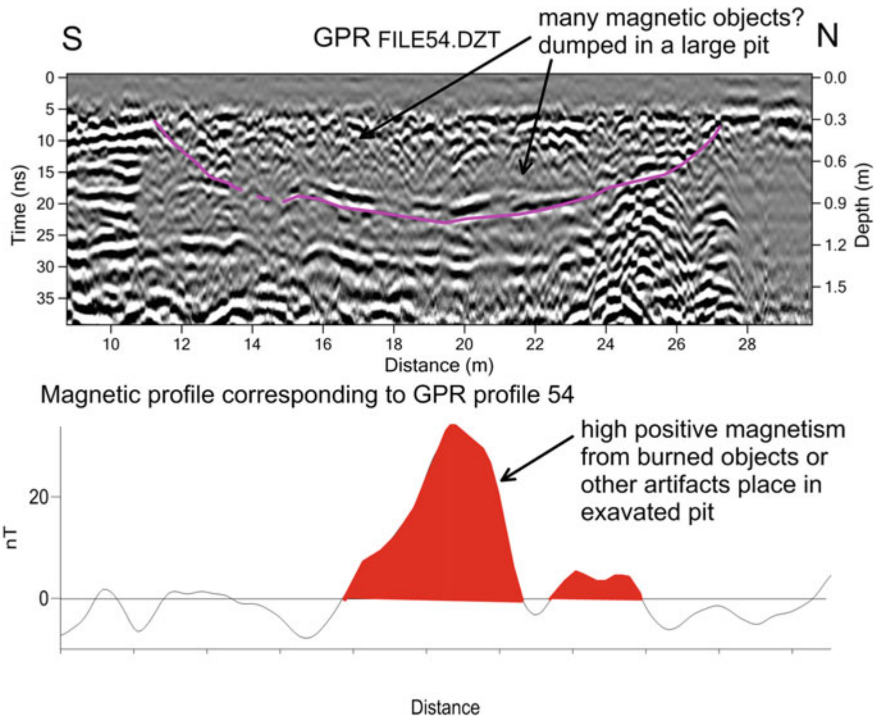

Fig. 5.6 GPR profile and associated magnetic readings showing a pit filled with magnetic material. Location of this profile is shown in Fig. 5.5

for the disposal of the burned remains of houses that were removed prior to the temple construction, then a second house was located in area #2. There may be other equally plausible hypotheses for these two holes filled with burned material, and perhaps future excavations will help in understanding this interesting human behavior that was undoubtedly related to burning in proximity to the nearby Roman temple.

A second area within detailed area #2 is a small feature that is on the eastern edge of the interior courtyard of the temple ambulatory (Fig. 5.2). This was not immediately visible in the magnetic map, and only visible with GPR once a third geophysical method was first employed. Kris Lockyear collected an electrical resistivity survey over this area using a RM85 system. Those data were used to produce a map displaying the interior portion of the temple complex, which has a very low resistivity (high electrical conductivity relative to the surrounding area in the grid). This likely means that for some reason (to be discussed below) this feature collected water (Fig. 5.7). While there is an interesting and readily recognizable large square feature in map view using resistivity, what is also interesting is a small (about 4 $\times$ 3 m in dimension) square structure along the eastern edge of the temple

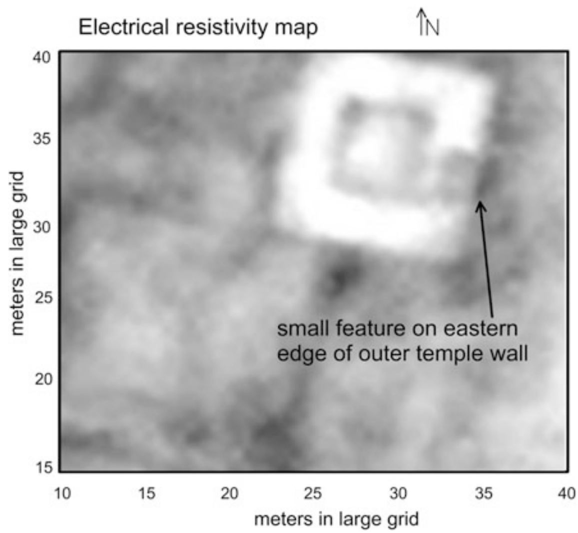

Fig. 5.7 Electrical resistivity map of the detailed area #2 showing very low relative resistivity values (white) within the temple complex walls. A small feature is visible on the eastern edge of the temple complex

complex outer wall. The resistivity map was used as a starting point to study this small rectangular feature using GPR and magnetics.

After closer examination of the GPR amplitude slice from 100–150 cm depth (Fig. 5.5), a high amplitude feature of indistinct geometry was visible at the same location as the small rectangular resistivity feature. It is so small that it would have likely remained un-interpreted using either GPR or magnetics when studying the larger features visible in this complicated buried cultural landscape. The GPR reflection profile 68 (Fig. 5.8) crosses this feature and readily shows very high amplitude "bowl-shaped" sedimentary units that fill up some feature that retained them. There must have been walls that held this sediment in place as the rectangular building filled up, but none of the GPR reflection profiles show those walls. They were probably constructed of wood that stayed upright for some time after the structure was abandoned, and therefore acted as a receptacle for sediment accumulation before they finally decomposed.

The sedimentary layers are visible as very high amplitude vertically stacked beds in the GPR profile (Fig. 5.8), which indicates that the filling did not take place at one time, but likely over many years during multiple depositional events, creating a number of layers, each of which reflects high amplitude radar energy (Conyers 2013: 47). In this profile the outer walls of the temple complex are also visible, and similar sedimentary fill units can also be seen on a larger scale, which filled in that larger receptacle of the ambulatory walls over time. Both these lines of evidence show that for a good deal of time after the Roman temple was abandoned, walls remained standing and slowly filled up with material. It was likely that sometime

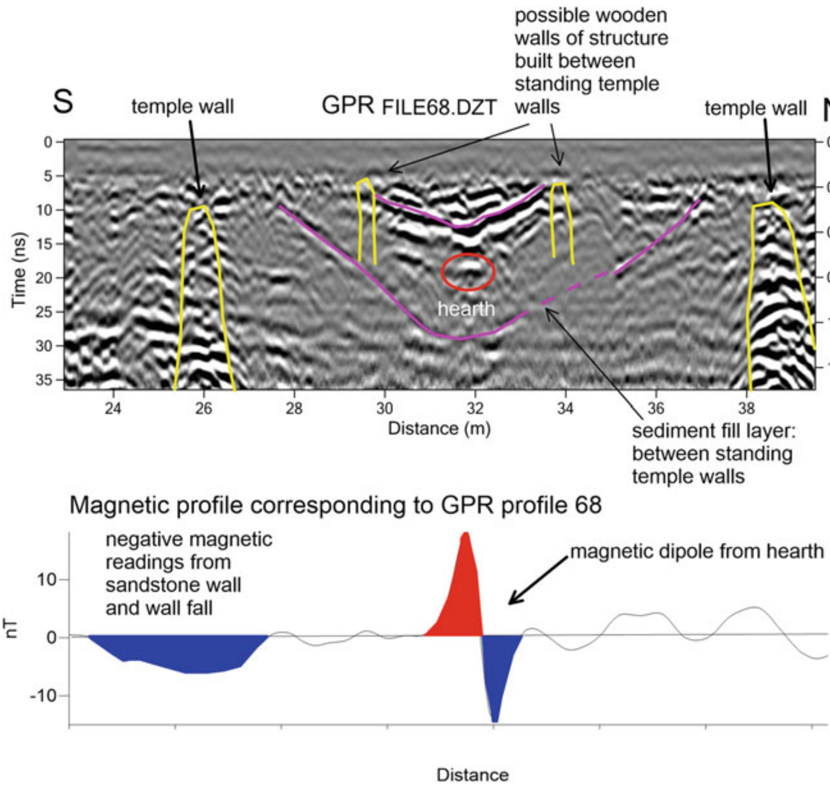

Fig. 5.8 GPR reflection profile 68, location of which is shown in Fig. 5.5. This profile shows the sediment fill layers within a small structure built on the eastern edge of the temple complex

after the Roman occupation people came back to this still standing temple complex and built a smaller structure, incorporating the eastern wall into that new small building.

5.3 Conclusions

The standing walls of the temple were presumably not destroyed to obtain building stone, and this structure is still colloquially known as "the fort" by local people as well as archaeologists and historians. Sometime over the long span that the temple walls stood, people built a wooden structure there, and after that was abandoned, both its walls, and the larger still-standing walls of the temple continued to fill with sediment. Those buried walls and the remaining Roman walls acted as a barrier to water movement, and even today retain enough water to give the interior of the temple complex (and the small structure within it) a low electrical resistivity due to this higher water saturation.

It is also interesting that directly in the middle of this small structure within the temple complex is a magnetic dipole, which correlated to the very bottom of the "bowl-shaped" depression visible in the GPR profile (Fig. 5.8). That area in the middle of this structure is likely a hearth, and its burning produced this very small magnetic anomaly due to its elevated thermally-induced magnetism.

These examples of magnetic and GPR interpretations (with the aid of resistivity mapping in one area) allow for the generation of some interesting hypotheses regarding people's use of this site during Roman time, and after its abandonment. One hypothesis is that Late Iron Age structures were burned and buried prior to the construction of the temple and its surrounding walled complex.

The so-called "fort" in local lore is actually a Roman temple, and just to the east were commercial or industrial buildings along a road to the east. Why there is no magnetic signature for burning within the temple or its walls during the time it was in use is somewhat mysterious. After Roman occupation ceased, people robbed some of the standing buildings for stone, and even "mined" into the ground to obtain these building materials especially from the large structures on the eastern edge of the grid. They did not destroy the temple complex for some reason. Parts of those walls remained standing until just recently when just their tops sticking out of the soil were recycled. The eastern wall of the temple complex was incorporated into a small building with a central hearth at some unknown time. That structure was likely constructed of wood and nothing remains of its walls to reflect radar energy, and it has no magnetic signature. The sediment that it retained, however, is higher in water saturation, making it visible in the resistivity map and its fill layers are prominent and easily interpreted in GPR reflection profiles.

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Chapter 6
Early Colonial Site in Connecticut

Abstract An early colonial farmstead in Connecticut was constructed in an area of rich farmland, surrounded on the north and south by rocky and swampy ground. The environmental features of this area were identified in some small excavations, and also by a comparison and correlation to GPR reflection profiles and magnetic readings across a large buried landscape. The individual geological units that allowed for a regional environmental landscape analysis could be defined in the GPR profiles with direct comparison to magnetic readings. The colonists built four houses with distinct cellars in one cluster of the study area, which are readily defined with GPR as incisions into the ground filled with sand and silt. To the south and north of the settlement was an environment that was less conducive for farming and Native American houses were discovered there using the GPR amplitude maps and reflection profiles. One of those native houses had been burned, and was readily interpreted using the magnetic maps superimposed on the GPR maps. It appears that from the geophysical mapping and some excavations that native people and colonists from England lived in close proximity to each other, but preferred different areas of the landscape for their houses, perhaps because of the resources they hunted, gathered or farmed.

6.1 Background to the Site

In the Connecticut River Valley along the eastern seaboard of the USA, European colonists began to move into the fertile farm land occupied by native populations in 1633 (Andrews 1889: 8). These first colonists were Dutch, who founded a trading post near present-day Hartford, and by the late 1630s English settlers arrived and had moved inland along the coastal rivers (Adams 1904: 34). Two small towns called Wethersfield and Glastonbury were founded along the Connecticut River on land that had been occupied by the native people of the Sequin tribe who had a sizable settlement called Nayaug nearby. The two very different groups continued to live in close proximity to each other peacefully until King Philip's War, which

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https://doi.org/10.1007/978-3-319-70890-4_6

began in 1675 (Grumet 1996: 122). This conflict pitted native people against the English colonists and their Indian allies.

The study area is in an agricultural field that has been minimally disturbed since the 17th century. Historical records show that this land was acquired from the inhabitants of Nayaug about 1640 by John Hollister and has remained in the hands of his descendants since that time (Glastonbury Records 1680). Permission to conduct geophysical surveys and excavations on the property were obtained from those descendants who still live nearby. Historic records and family oral histories indicate that the original settlement of the John Hollister family was located in this field, and many surface artifacts including pipe stems, pottery and other artifacts have been found there over the years. Just to the south of the property archaeological excavations have shown the presence of a pre-Colonial Native American settlement showing a long period of human occupation nearby (Marteka 2015). Historic records show that a large flood inundated this area sometime in the early 18th century, and about that time the descendants of Hollister moved to the northeast to higher ground. The land has been used for agriculture ever since.

A preliminary GPR survey of the area was conducted by Peter Leach in the summer of 2015, which showed the possible presence of cellars that had a square shape, and it was suggested they might be the remains of the original Hollister family settlement. His work was followed up by GPR and magnetic surveys by Maeve Herrick and Jasmine Saxon of the University of Denver, with archaeological excavations based on those results led by Brian Jones, the Connecticut state archaeologist, and many local volunteers.

6.2 Data Collection and Analysis

The magnetic data were collected with a Bartington twin-prove magnetometer. A map of these readings shows a great deal of modern metal objects at or near the surface (Fig. 6.1). In particular there is a roughly rectangular northwest-southeast trending concentration of dipole anomalies that corresponds to the location of an historic tobacco drying barn that was built here in 1934 and torn down a few decades later. Those small dipoles are likely nails and other iron objects associated with that barn. Two other concentrations of metal magnetic anomalies are visible in this map, one on the northwest and northeast edges of the grid, where recent metal trash is still visible on the ground surface. On the southern side of the grid a number of linear positive and negative features are prominent, which are glacial moraine and fluvial channels deposited at the end of the last ice age (Figs. 1.2 and 1.3). An historic road leading from what was a ferry dock along the river to the west was located on that glacial moraine feature, presumably because the ground along it was hard, raised and well drained (Fig. 6.1).

The GPR amplitude slice-map from 15–20 ns (about 50–75 cm depth) that covers a portion of the magnetic map, displays many interesting cultural features in this study area (Fig. 6.2). The depth slice shown in Fig. 6.2 includes the historic

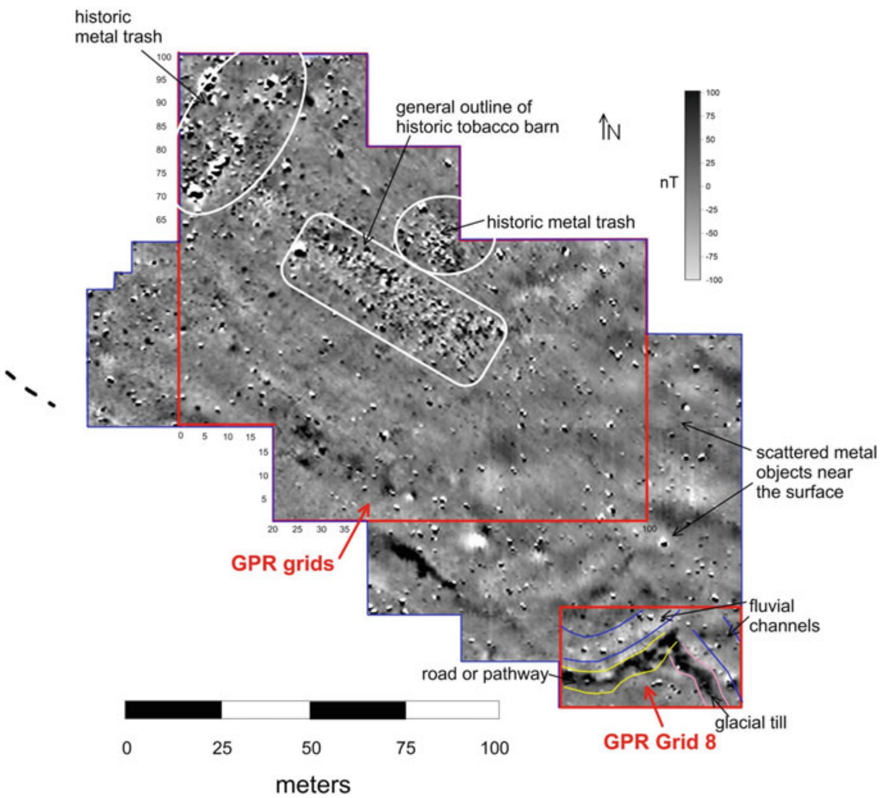

Fig. 6.1 Magnetic map with the GPR grids

buried living surface, which was a soil unit sitting on fluvial and glacial lake sediments (Fig. 6.3). The buried surface is particularly interesting when visualized in the GPR amplitude slice as it displays concentrations of many high amplitude reflections produced from stones that are likely construction debris and artifacts from the time of occupation (Fig. 6.4). The concentration of these materials in the 50–75 cm depth can be seen surrounding four distinct house cellars, which are visible as rectilinear areas of no reflection in the amplitude map. The cellars had houses built over them and after abandonment valuable construction material was likely salvaged before the structural remains were burned and covered over. It is also possible that the abandonment of these houses and their sub-floor cellars happened after one of the large floods in the first decade of the 18th century as the filling sediment is fine grained sand and silt consistent with sediment derived from the nearby river. The cellar fill is not reflective to radar waves and shows up as areas of no amplitude in the amplitude map (Fig. 6.2).

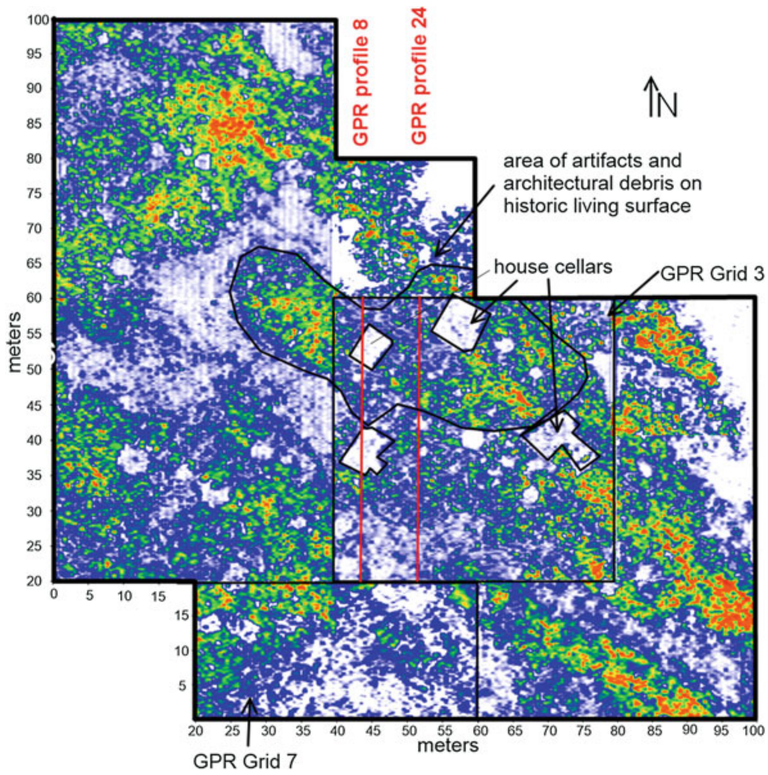

Fig. 6.2 Amplitude map of the GPR reflections from all contiguous grids in the study area from 50–75 depth. This slice encompasses the historic living surface and displays house cellars, artifacts and architectural materials around the house locations

There are many other high amplitude areas in this GPR slice-map where the resampled slice crossed geological boundaries (Fig. 6.2). Those geological materials are visible as variously shaped regions where the Ice Age glacial till and post-glacial lake and fluvial deposits are near the surface.

A GPR reflection profile across this living surface containing reflective artifacts shows a distinct build-up on the late 1600 s living surface (Fig. 6.4). Many metal objects closer to the surface are also visible as distinct point-source hyperbolic reflections in this profile, derived from the iron remains of the 1930s era tobacco barn that stood here and which show up prominently in the magnetic map (Fig. 6.1). What is most interesting about the GPR reflection profiles that cross the high amplitude reflection area visible in the 50–75 cm amplitude slice (Fig. 6.2) is that this layer of materials sitting on the buried soil unit is concentrated between and around the house cellars, which is consistent with an anthropogenic deposit.

Much of the interpretation at this site was possible using only the GPR data, the integration of the individual GPR reflection profiles and a few excavations that

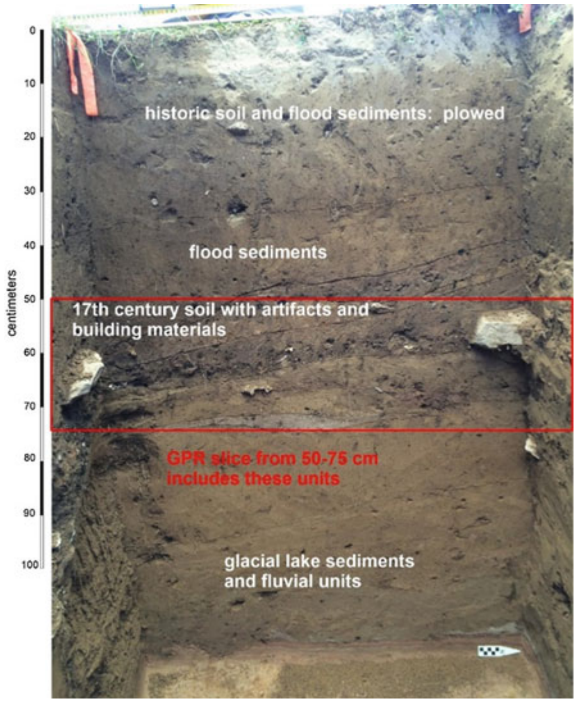

Fig. 6.3 Soil and sediment profile showing the 50–75 cm depth slice as it cuts through a buried soil unit containing large stones and other artifacts from the 17th century houses nearby. This buried soil is overlain by flood sediments deposited at the time this site was abandoned, and perhaps afterward

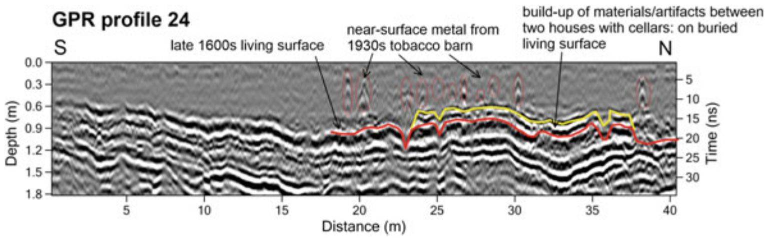

Fig. 6.4 GPR reflection profile crossing the area where there is a concentration of building materials and artifacts on the late 1600s living surface

reveal stratigraphy and artifacts at important depths. The mapping shows a concentration of European houses in one area, with four distinct rectilinear cellars. Many other circular and oval features are also visible in this amplitude slice near the cellars, which could be storage pits or wells. One appears to be an oval semi-subterranean house floor possibly constructed by native people who are known to have occupied this area before and during the time that the English colonists arrived. Some other remains of Indian dwellings nearby will be discussed below, which were found to the southwest in Grid 7 (Fig. 6.2).

One profile that crosses two distinct cellars is illustrative of the remains of these distinctly shaped English dwellings (Fig. 6.5). The cellars were cut into the fine-grained fluvial and lake sediments deposited in this area throughout the early Holocene period (Stone et al. 2005). Stones were used to line the cellars, as was documented in excavations, and floors were then constructed over the top. Simple wooden structures with chimneys were then raised over the cellars, with access to the cellars by a trap door in the floors. A GPR profile shows how these cellars were stepped, with some ledges around their edges (Fig. 6.5). The magnetic readings that correspond to the cellar area indicate that both of these incised features were filled with burned material, and perhaps some iron objects. Distinct layers of fill sediments and debris are visible in many of the GPR reflection profiles in areas where the magnetics also show very high positive readings. This is evidence that these houses may have been intentionally burned at the time of abandonment. It is possible that one or two were accidently burned, but all four of these houses show very high magnetic fill materials in the cellars, so it is unlikely that all were incinerated accidently. They may all have been burned deliberately to reclaim the land for farming.

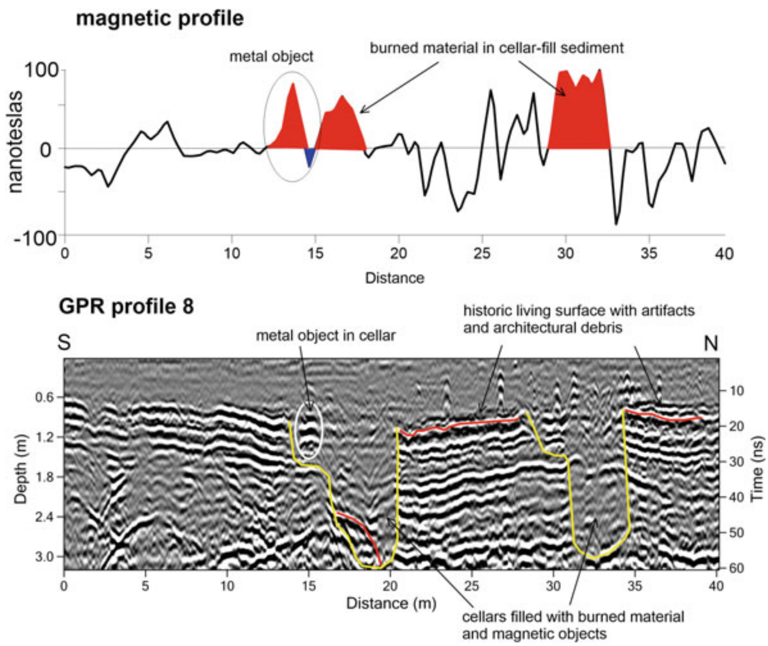

Fig. 6.5 GPR reflection profile in Grid 3 showing two cellars, with corresponding magnetic readings indicating they are filled with burned material

The magnetic map, when interpreted singularly, is not helpful at defining these buried cellars filled with burned materials (Fig. 6.1). The plethora of surface metal from the 1930s tobacco barn obscures this grid with many dipole anomalies that just happens to be directly on top of many of the cellars of interest. It is only when individual GPR reflection profiles are interpreted and magnetic values are used to interpret the types of materials visible in the profiles that these two data sets become complimentary.

In this analysis of the English house cluster the magnetic and GPR datasets show that 17th century settlers built 4 rectangular houses with deep cellars in one area. These four houses must have been dwellings for more than one family. Perhaps John Hollister's growing family over a few generations built these houses in sequence as their numbers grew. The building sequence could possibly be studied with more excavations into the cellars accompanied by an analysis of artifacts and their styles contained in them, which could yield possible ages of each.

Excavations of one cellar in 2016 (the northwestern cellar visible in Fig. 6.6 and the cellar on the right in the profile in Fig. 6.5) yielded a large variety of very interesting artifacts and materials. Among the artifacts recovered were a variety of 17th century European ceramics including many lead-glazed earthenware vessels, German stoneware jugs, Delftware serving platters, apothecary jars, and a few English ceramics produced in the Midlands. Less common objects appear to have been manufactured in Italy, all of which show that the Hollister family was doing well economically and was connected to the incipient trade patterns that were initiated with Europe early in the history of Colonial America. Many clay pipes and pipe stems were found, some manufactured in England, and others that appear to

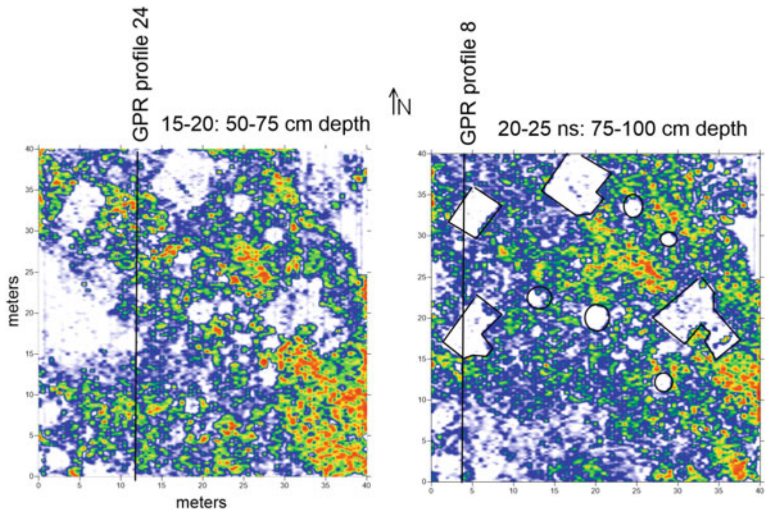

Fig. 6.6 Grid 3 amplitude maps from 50–100 cm depths. Location of Grid 3 is shown in Fig. 6.2. The deeper slice displays the outlines of the features cut into the sediments, with four rectilinear cellars, and a number of round holes that could be wells or storage pits

have been produced locally. A wide variety of other objects inducing knives, nails, brass objects, gun flints and balls and food remains were also recovered. The animal bones were from pigs, sheep and cows, but also wild deer, bear, turtles, birds and fish, with some marine organisms including oysters and clams. The inhabitants of this apparently isolated farmstead in what was a very rural household in the 17th century were apparently eating quite well, and had established trade patterns with people on the coast who were in regular contact with Europe.

What makes this site even more interesting was the recovery of hundreds of fragments of Indian pottery including a few large decorated cooking vessels. This indicates that the inhabitants of this house were in close contact with the local native people, and those Indian people either traded with the English colonists, or they perhaps even lived together in this dwelling. Its discovery show that even in this area far from the main trading centers on the coast, immigrant people were likely socially integrated in some way with the Indian inhabitants, while still very much in economic contact with other colonialists, which has not been documented elsewhere (Lavin 1985, Vaughan 1979).

To the south of the English house cluster are the remains of three pit structures that are oval in shape, filled with non-reflective sediment (Fig. 6.7). These features were incised into the underlying fluvial sediment, which appears as very high

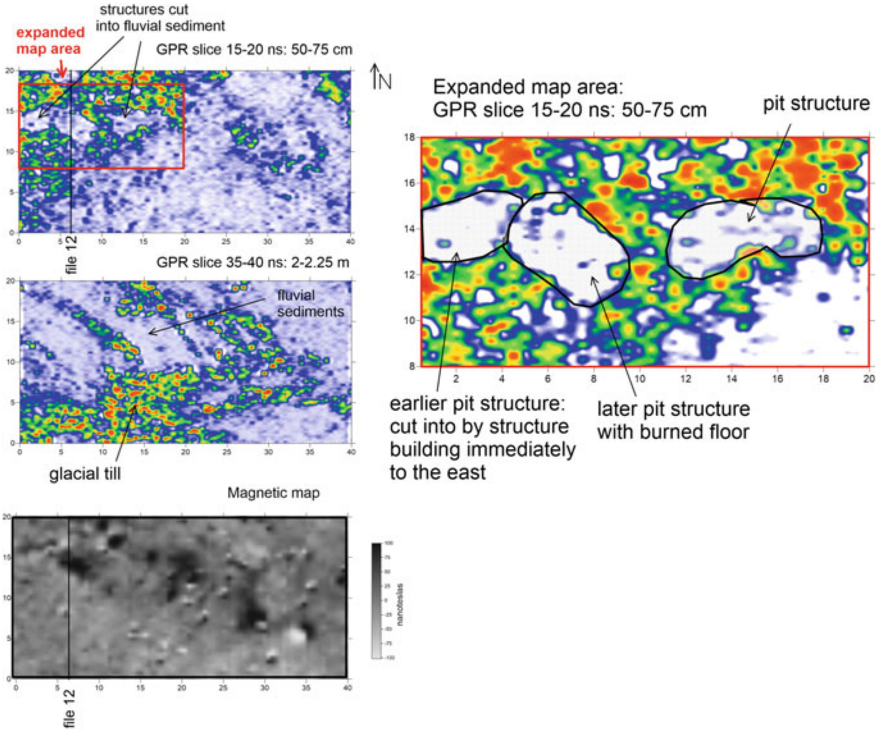

Fig. 6.7 Grid 7 GPR amplitude maps and magnetic map of the area over the three pit structures. An expanded high resolution grid of the 50–75 cm depth is shown on the right. Location of GPR reflection profile 12 (Fig. 6.8) is shown

amplitude reflections on the 50–75 cm depth slice. This area is underlain by glacial till visible in the 2.2–25 m depth slice of Fig. 6.7. The local indigenous inhabitants of this region lived in one room oval shaped dwellings, covered with branches, daub and sometimes sod (Grumet 1996). It is likely these oval dwellings found with GPR are the remains of three of these dwellings. Excavations in 2017 of one of these oval features recovered a large deer antler still attached to the skull associated with other 17th century artifacts. This is good, but still preliminary, evidence that these dwellings were likely contemporaneous with the English housed to the north.

An expanded and high definition amplitude slice covering these oval features from the 50–75 cm depth shows that on the western edge of the grid one feature cuts through an earlier constructed one (Fig. 6.7, expanded map). This indicates there was some length of time that people lived here and they likely abandoned one structure and then later constructed a new one in the same general location, partially destroying the earlier dwelling. Excavations in 2017 uncovered large post holes that must have supported a sizeable roof over one of these houses showing that they were inhabited for some period of time and were not just short-term occupations.

While the magnetic map of Grid 7 alone only appears to show one of the pit structures (Fig. 6.7) the data from those readings can help interpret the GPR profiles in a way to further understand these structures. A GPR reflection profile across the middle pit structure (Fig. 6.8) shows it to have been incised about 50 cm or so into the fluvial/lake sediments that are close to the surface in this part of the study area.

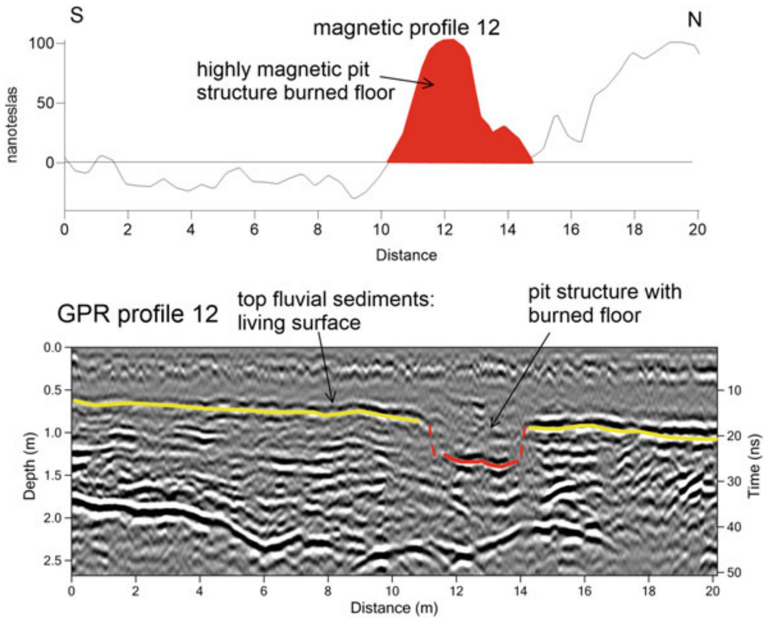

Fig. 6.8 GPR profile 12 in Grid 7 (location in Fig. 6.7). A pit structure was constructed by cutting into the underlying sediments. It has a distinctive floor

It has a very distinct floor, and the magnetic readings associated with this GPR reflection profile show that it is highly magnetic. As only this structure shows these high positive magnetic readings, and not the two adjacent to it, it is likely to have been burned during one event. This is the reason that this middle pit structure can be seen on the magnetic map and not the other two (Fig. 6.7).

The combination of GPR and magnetic analysis in Grid 7 shows that there were at least three Indian pit structures located in this area, one of which was cut into a pre-existing house and then later burned. One similar structure is also found to the northeast of the colonists' houses. The age of all these houses is not known, and no excavations have taken place there. If they are contemporaneous with the European farmstead just a 50 m or so to the north then it might explain the interesting collection of Native artifacts found in the one excavated cellar, which held both European and Indigenous materials. This opens up the possibility that these two very different cultural groups were living very close to each other in presumably peaceful conditions, but still segregating themselves with respect to where they resided. While this is speculative at this time, it opens up the possibility that at least early in the Colonial Period of European occupation there were interesting, complex and perhaps complementary relations between these two very different people.

Another interesting aspect of this study is placing these two potentially segregated communities (at least with regard to habitations) on a map showing what the landscape was like in the 17th century (Fig. 6.9). An analysis of the bedrock units in Grid 8 (Fig. 6.1) on the southern edge of the study area shows a linear band of

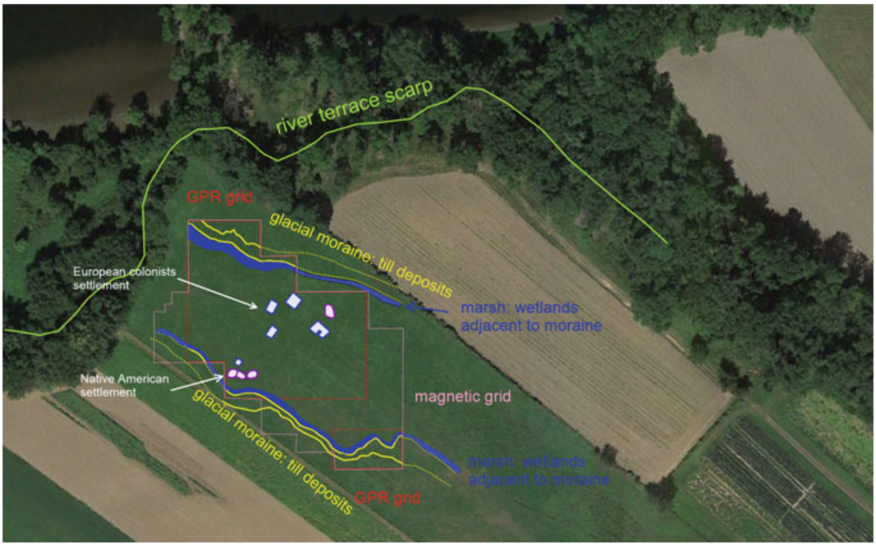

Fig. 6.9 Aerial photo of the site showing the Connecticut River to the north and the location of the lower terrace scarp. The Native American and European settlements discovered with GPR and magnetics are shown, with the location of the bedrock features visible using both geophysical methods displayed

highly magnetic glacial till trending roughly east-west (Figs. 1.2 and 1.3). On the margins of this coarse sedimentary body are fluvial sediments, which are likely the remains of glacial outwash streams that flowed between the raised glacial sediments (Fig. 6.9). In many post-glacial environments these low areas become marshland after the stream water ceases to flow from the melting glaciers, and these areas continue to be swampy for long periods of time (Stone et al. 2005). The location of the Indian pit structures is just to the north of where the glacial moraine and associated low swampy areas were (Figs. 1.2 and 1.3). This small Native American settlement may be significant, as it was close to resources that could be obtained from hunting and gathering along these wetlands adjacent to the moraine.

The Europeans, however, preferred a very different location for their houses where the ground was drier, and cellars could be dug without risk of hitting the water table. They therefore preferred the area to the north where their digging only encountered fine-grained dry fluvial sediments (Fig. 6.9) and not the rocky glacial deposits or the marshy wet ground. To the north of the European farmstead a second glacial moraine is also visible with GPR mapping, showing that the location chosen for their farms was between two linear areas of raised rocky glacial ground with associated marshy lowlands. This was no doubt a deliberate decision by the colonists, and their living quarters were also placed in the middle of the best drained fertile soils. The choice of where these two different people chose to live shows their attraction to the resources they considered important. The Indian people while partially agricultural were also attuned to the resources that could be gathered and hunted near the wetlands. In contrast, the Europeans were partial to the best farmland and also to well drained ground where cellars were built for the storage of food items. They therefore chose a very different location on the landscape.

6.3 Conclusions

This project allowed for the discovery and interpretation of a very important colonial settlement in an area of New England that has been completely undisturbed since the early 1700s. The discovery of four European cellars, and other associated features, shows that this was a locus of the initial settlement of English people. The GPR analyses, tied to stratigraphic information obtained from excavations, shows that these colonists chose a well-drained area between two rocky moraines and associated low marshy areas. Through a combination of GPR profile analysis, amplitude slice-maps and magnetic readings it was possible to map the extent of these geological features, along the north and south edge of the study area and place people within this historic landscape.

Analyses of the house cellars in GPR reflection profiles show that they were mostly filled with fine-grained sediment, but the magnetic readings show that some of that fill had been burned. This suggests abandonment of these houses was deliberate and that the remains of the burned dwellings fell into the cellar holes. The cellars are filled with a wealth of artifacts and food remains, showing these people had a rich and varied diet, and were quite wealthy as they had many fancy and prestigious eating and cooking utensils. To the south of the colonial cellars are three Native American oval pit structures, which were likely constructed in this area of the site to be close to the wetland resources they preferred. One of the houses had been burned and had also been constructed into a previously built house, showing multiple habitation periods there.

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Chapter 7
Medieval Site in Ireland

Abstract A Medieval village, of probable Anglo-Norman age, was discovered buried in a field east of a still-standing castle in western Ireland. This village is composed of houses that were enclosed by ditched and berms that were likely property boundaries but also served to drain the wet ground for other activities. The ditches are readily visible with magnetic mapping, and the central hearths of houses stand out as distinct positive magnetic anomalies. The house floors and other built features on this cultural landscape are visible using GPR reflection profiles, and their interpretation helps in understanding many of the magnetic features through the area. A structure, which is likely a crannog, is visible in both magnetic and GPR amplitude maps in what is a marshy area today. The GPR images of this building show a distinct floor and central hearth, with posts and a stone wall that supported it. The magnetic readings show part of its floor outline, and the central hearth. An overall analysis of the human presence on this broad landscape east of the castle indicates that the people who lived there were connected to the ruling elite in the castle by a road leading through their village, heading directly to the castle gates. Those people may have played a role in the construction of the castle, or provided products and services during the time of the Anglo-Norman invasions and subsequent occupation.

7.1 Background to the Site

A number of large grids of GPR and magnetic data were collected to the east of the Ballintober Castle in County Roscommon, Ireland. The goal of this project was to explore for, map and begin to understand the inhabited precincts around the castle where workers associated with the castle might have lived. Ballintober Castle is a privately owned stone-built complex owned by the descendants of its ancestral occupants, the O'Conor family. It appears to have been built at the start of the 14th century by the invading Anglo-Norman Earl of Ulster, Richard de Burgh and then passed into O'Conor hands about 100 years later.

L. B. Conyers, *Ground-penetrating Radar and Magnetometry for Buried Landscape Analysis*, SpringerBriefs in Geography,
https://doi.org/10.1007/978-3-319-70890-4_7

Ballintober Castle stands on elevated ground just north of the present village of Ballintober (Fig. 7.1). The surrounding land is today used for pasture and some farming activities with low hills to the north and east, peat bogs and marshes to the west and low lying land to the south.

There are a number of historical and anthropological questions of interest in this research that revolve around what appears to have been a contested 13th through 15th century landscape. It pitched conquering Anglo-Norman lords who resided in the castle against indigenous Gaelic people who likely lived in the countryside (McNeill 1997). The complex power relationships that were being negotiated and played out during this period of time can be discerned in the historical documents, but little is understood about how these were being established with regard to the more common people who performed the everyday tasks of society. The approach used in this research is to test ideas about economies, society, culture and the relationships that were imposed on and sometimes accepted or rejected in part by the people of western Ireland. This research must begin with first finding their settlements in the present-day pasture land that has been relatively undisturbed for centuries. By examining the spaces where people resided and worked around the castle an understanding of the economic and cultural activities that occurred there can be related and integrated with those of the Anglo-Norman rulers who lived in the castle. This is the beginning of a process necessary in developing ideas about people, cultural change, and dominant and submissive (or perhaps resistive) groups of people during this turbulent period in Irish history. To date the presence of more humble dwellings around castles has been assumed, but archaeologists have been frustrated by the absence of visible remains for most village sites in Ireland (Brady 2009).

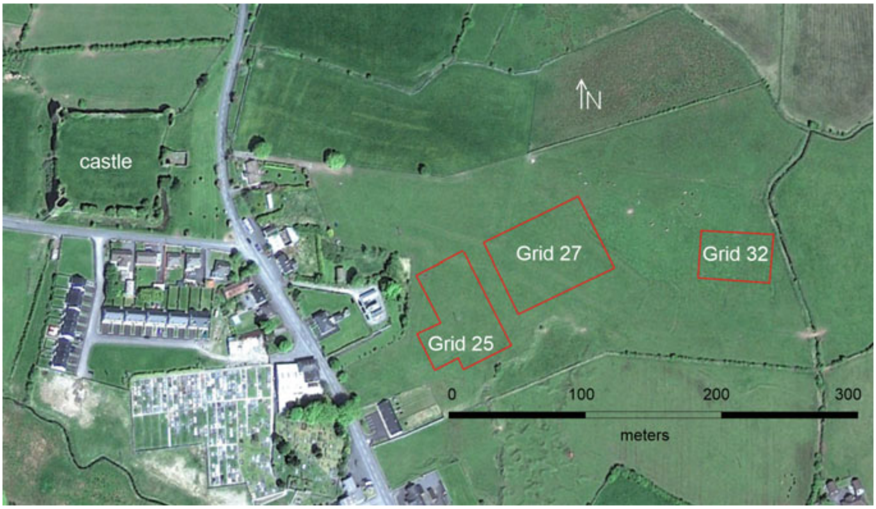

Fig. 7.1 Base map of the GPR and magnetic grids discussed here east of the village of Ballintober and the Ballintober castle

7.2 Data Collection and Analysis

The GPR data sets were acquired with a GSSI SIR-3000 system and 400 MHz antennas. Magnetics data were collected using the Bartington dual gradiometer system. The ground here is excellent for both methods as it is flat, treeless and therefore surveys can be easily performed with data collected in large grids, which is excellent for geophysical landscape analysis. Bedrock in this area of Ireland is limestone, which has a low magnetic susceptibility, and therefore most positive magnetic anomalies that are discovered can usually be interpreted as iron objects, burned features or organic-rich deposits, all of which have important cultural implications. Common in the area is a poorly sorted gravel and cobble till unit that was deposited on bedrock during the retreat of the glaciers. The sediments and soils overlying the glacial till are also electrically resistive, which allows radar energy to pass up to 3 m in this ground. The abundant rainfall makes this ground wet and sometimes water saturated, which slows the radar waves as they travel but does not appreciably attenuate them.

In the summers of 2015, 2016 and 2017 more than 120 grids of GPR and magnetic data of various sizes were collected in the fields to the east of the castle. Only three (25, 27 and 32) will be discussed here (Fig. 7.1). The ultimate goal of this project is to survey all the lands surround the castle that are possible in the coming years.

Grid 27 is much like many of the other grids of data to the east of the castle (Fig. 7.2). The magnetic map shows many positive magnetic features that are long and straight, which spatially appear like buried walls or ditches. Areas between the walls are relatively "quiet" magnetically with some small dipoles and a few other larger magnetic features. A cursory analysis of the GPR amplitude map over the same grid also displays high amplitude features roughly parallel to the linear magnetic anomalies, but also a variety of other geological and cultural features of unknown origin.

One of the first goals of the project was to understand the most notable magnetic features, the long linear positive anomalies (Fig. 7.2). An area was chosen to the east of the castle to test one of these features with an excavation trench crossing this type of anomaly at a right angle. The GPR reflection profile across this linear feature shows it to be it as a distinctive ditch parallel to a constructed berm (Fig. 7.3). The positive magnetic values are associated with the ditch, and the negative with the berm. In the magnetic maps the positive feature (shown in black on the magnetic map in Fig. 7.2) is more visible, but the negative values (white) are still there but subdued. It is only when the individual magnetic values are extracted from the dataset and compared with the GPR reflection profiles where these features are visible in two-dimensions, can this correspondence can be understood. An archaeological trench across the ditch and berm feature shows exactly what is visible in the GPR profile, and the origin of the magnetic linear features can be interpreted.

In this very wet area of western Ireland, ditching fields that are subject to waterlogging is necessary to produce ground that can be planted in crops not

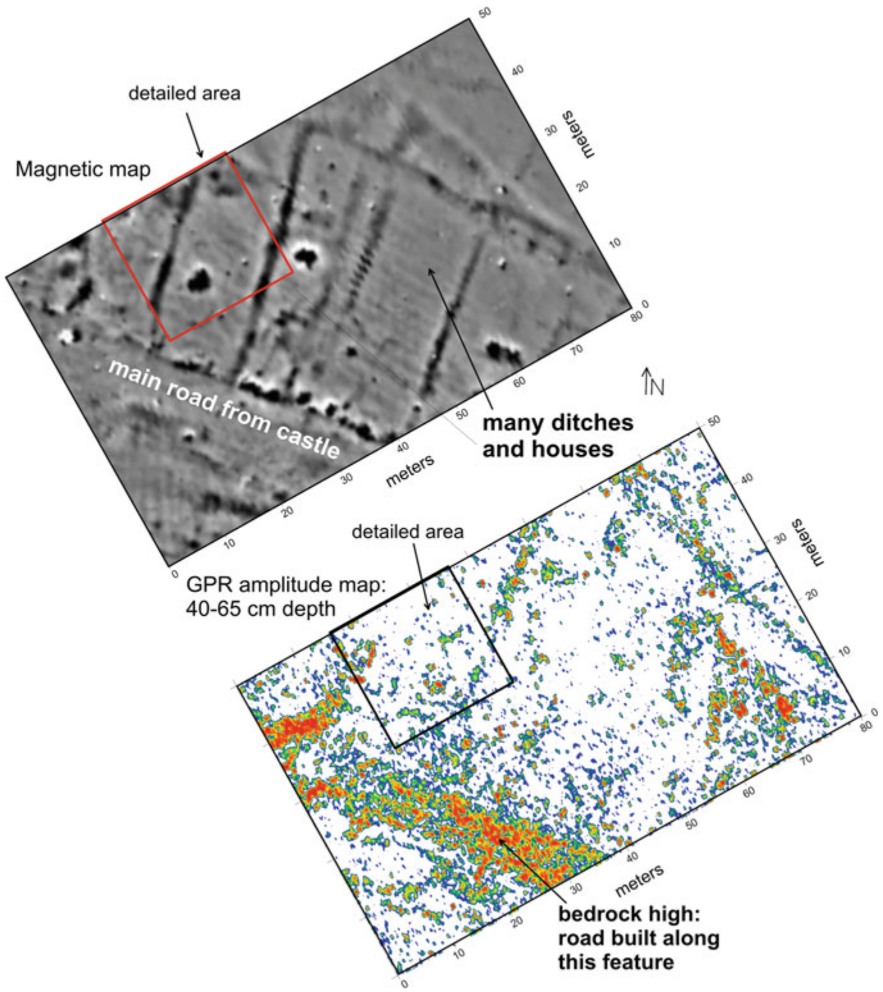

Fig. 7.2 Grid 27 east of the castle displaying many linear features in the magnetic map, and a variety of geological and archaeological features in the GPR slice-map

conducive to extremely wet conditions. These types of agricultural soil maintenance systems are still in use in Ireland today and allow otherwise wet or waterlogged soils to become available for some forms of agriculture. The berm was likely constructed with materials excavated from the ditch and then piled upslope from it during construction. This berm (Fig. 7.4) consists of the local weathered limestone that contains some limestone rocks and also limey and clayey subsoil that has a very low magnetic susceptibility and therefore shows up on magnetic maps as negative readings. The ditch that filled with organic matter over time is therefore displayed as positive magnetism.

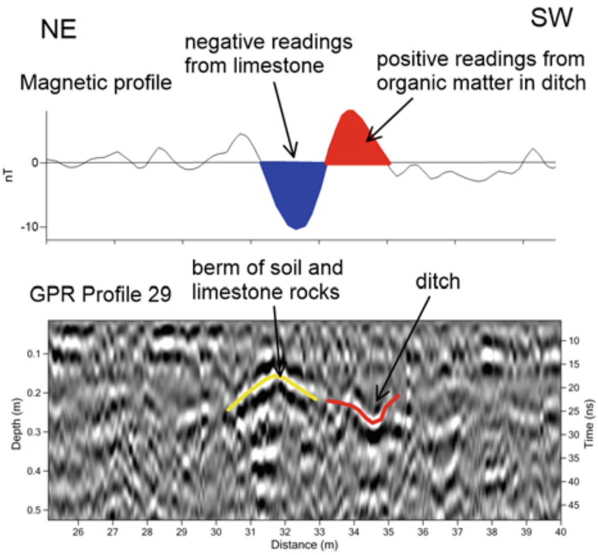

Fig. 7.3 Magnetic and GPR reflection profiles crossing a ditch and berm feature. The berm, composed of limestone and limey soil is negatively magnetic, while the ditch, filled with organic material, is slightly positive. Both are visible as distinct reflections in the GPR profile

Fig. 7.4 Excavation trench across a berm and ditch shows exactly what is visible in the GPR profile in Fig. 7.3. The berm upslope from the ditch was likely constructed from the material removed from the corresponding ditch

Once the origin of the linear magnetic features was understood, one area of Grid 27 was chosen (Fig. 7.5) for detailed analysis (location of the detailed grid shown in Fig. 7.2). This area displays a very subtle positive outline of what was thought to be a house with a very strong positive magnetic anomaly in its middle. The house is within a ditch and berm boundary. This feature was a dwelling with a central hearth. The very subtle outline of a round-cornered rectangle is subtle but still visible in the magnetic map. This magnetically delineated structure may be displaying a higher organic concentration along its margins where the remains of the superstructure or roofing material was deposited and then decomposed after the structure was abandoned. The GPR amplitude map does not display these same features, other than a general concentration of high amplitude point-sources derived from stones in the central hearth. A rectangular building or stacked stones to the west of the house visible with GPR (Fig. 7.5) is not in the magnetic map, and is likely the remains of a stone structure composed of locally obtained rock, whose composition is not appreciably different magnetically from the surrounding ground. No evidence of burning can be seen within this stone feature so it is unlikely to be a habitation structure. While it appears to be shaped like a building, it may be cut stones to be used for more substantial construction elsewhere.

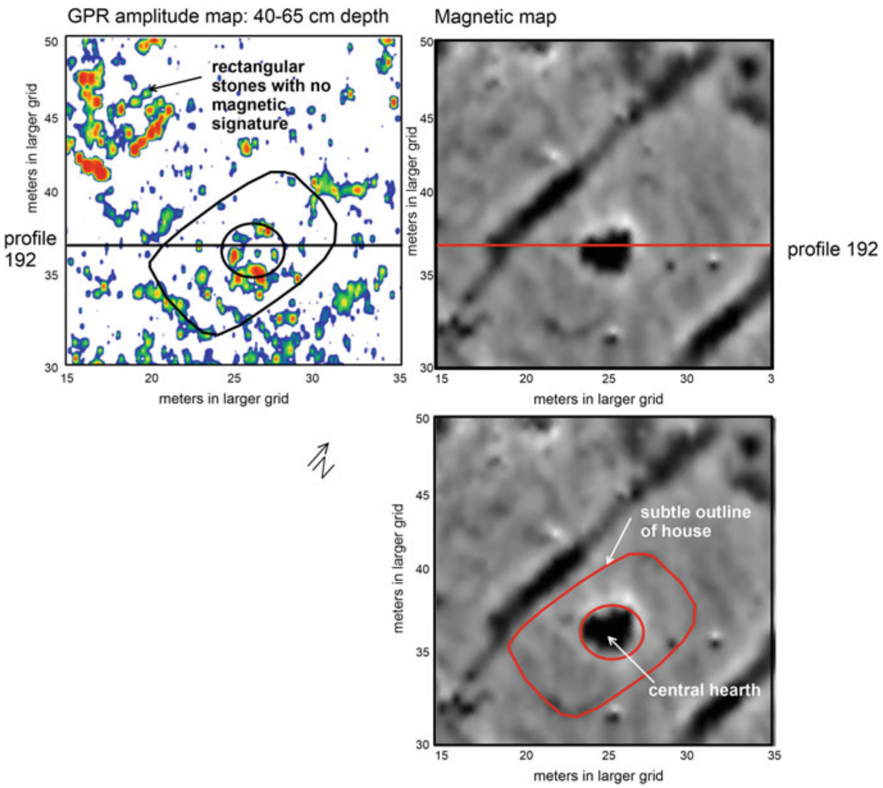

Fig. 7.5 Detailed area of Grid 27 showing a house with a central hearth within a ditch system

A GPR reflection profile (Fig. 7.6) crossing the house visible in the magnetic map (Fig. 7.5) shows the ditch on the west, but no associated berm. This ditch has a positive magnetic signature, as expected. The house floor is quite visible in GPR reflection profiles as a sloping planar surface, with multiple stacked high amplitude reflections that could represent multiple floors that were baked due to burning. The floor was then repaved and perhaps burned again. Or each could be just remodeling events over time. A portion of the floor on the north was not presumably subjected to burning and has a negative magnetic signature. This portion of the floor was likely composed of the typical clay found in this area.

The central hearth is much higher in magnetism and its rounded appearance in both the magnetic and GPR amplitude map is consistent with a stone-lined feature on the floor of the house. Perhaps areas of the floor near the hearth were also periodically burned producing the prominent horizontal surface seen in the GPR profile in Fig. 7.6. The areas of the floor away from the hearth remained as unfired earthen floor.

An analysis of the remainder of Grid 27 (Fig. 7.2) shows three other ditch-bounded enclosures that have similar houses within them. All have central hearths, and very subtle outlines of rectangular houses similar to the one shown in Fig. 7.5.

To the south of the ditch-enclosed houses in Grid 27 (Fig. 7.2) is a wide negatively magnetic linear feature that has a very subtle surface expression. This feature is a road that leads almost directly to the castle. The GPR amplitude map shows a perfectly corresponding high amplitude planar feature along this road. It was excavated and the positive magnetic anomalies south of the road were found to correspond to a ditch. Parallel to it is a flat-topped berm composed of compacted clay and silt excavated from the glacial till unit found throughout this area.

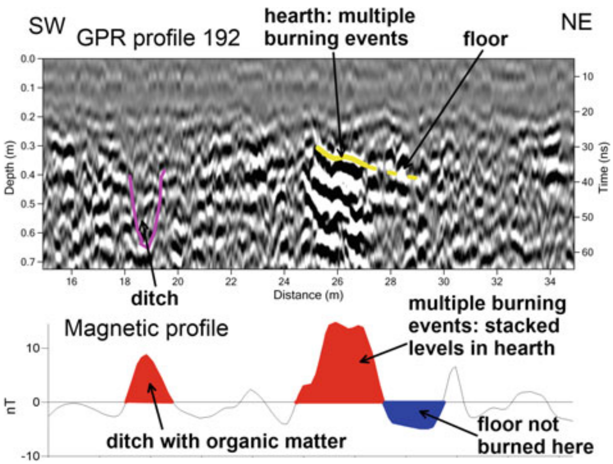

Fig. 7.6 GPR reflection profile and associated magnetic readings crossing the house floor shown in Fig. 7.5. The ditch is visible as an area of positive magnetism

The GPR reflection profiles crossing this road indicate that limestone bedrock sub-crops just below the surface soil along the road and the natural bedding planes are included in this slice (Fig. 7.2) producing the high amplitude linear feature. Because bedrock is very close to the surface here it would have been the reason why the road was located there as it is harder, better drained and would make a natural road surface.

People who inhabited this area naturally chose the poorer rocky ground for the road, and the more agriculturally productive land to the north for their fields and habitation structures, likely surrounded by gardens or pasture. Each of the houses was built within the ditches that were constructed to drain this otherwise very wet ground. The people who lived in these houses were likely connected with the castle in various ways and could travel there easily along the road, but there is no evidence of widespread agricultural land adjacent to their houses. There is some ditched agricultural land identified by GPR and magnetic mapping to north and south of Grid 27 that has no evidence of houses, which will be discussed below. Evidently there was a small community of people living along the road who either worked the nearby agricultural land, herded animals that were moved to outlying pastures, or perhaps had other duties within or in close proximity to the castle to the west. A total of 30 of these ditch and berm delineated house plots have been found along the road to the east of the castle.

An adjoining grid (#25) of GPR and magnetics was studied just to the southwest of Grid 27 (Fig. 7.1). This grid displays similar ditch enclosures with possible houses within the ditch boundaries as seen elsewhere (Fig. 7.7). House locations can be identified by the very subtle positive magnetic readings around their outside walls, just as the house shown in Fig. 7.5. All include central hearths that are visible as large positive magnetic anomalies, and are quite visible features (along with the ditches) in the magnetic map. As many as 7 houses with hearths are visible in this grid. One area was chosen in Grid 25 for detailed analysis (Fig. 7.8). Within this smaller grid is a house that is a different shape than those to the north of the road. It is square with no rounded corners, and contains a central hearth. It may have been constructed of wooden planks for walls. To the south of the house along its wall is a linear highly magnetic feature, with all positive magnetic readings. This magnetic anomaly is exactly the same length as the walls of the structure.

The house chosen for detailed analysis (Fig. 7.8) is almost perfectly square, in contrast with the houses in the other ditched enclosures in Grid 27 (Fig. 7.5). To its west is an enigmatic GPR feature that could be a stone structure or stacked stones with no magnetic signature, similar to that near the house in Fig. 7.5. It is noteworthy that the shape of the houses in Grid 25 south of the road are subtly different than those to the north. They have square instead of rounded corners. This may be coincidental, but if excavations show other differences in artifacts or architecture, geophysically defined house shape may prove to be a way to identify different people or neighborhoods. Perhaps house shape has something to do with the functional needs of the occupants or it could be just a preference based on the history of different cultural groups who came here from different areas of Ireland or overseas. This is interesting, but very speculative at this point. If nothing less, it is

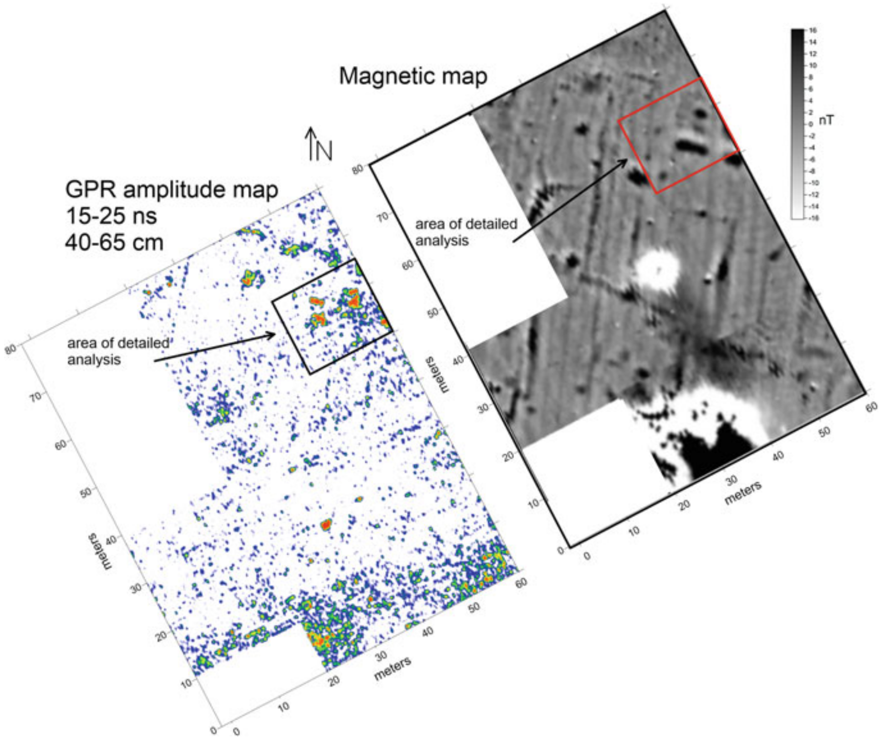

Fig. 7.7 GPR amplitude map and magnetic map of Grid 25 (location of which is in Fig. 7.1) that displays more ditch-enclosed land boundaries containing houses with central hearths. One area of detailed analysis is shown below in Fig. 7.8

an example of how geophysical mapping could readily identify areas where different people lived over a large inhabited landscape with no digging necessary.

The high positive magnetic anomaly just to the south of the house was puzzling when first viewed in the magnetic map (Fig. 7.7). This anomaly appeared to be larger than the other visible central hearths, and was exactly the same length as the southern wall of the house. There is no representation of this feature in the GPR amplitude map, but a reflection profile crossing it (profile 208 location shown in Fig. 7.8) shows it to be a well-defined 2 m wide trench (Fig. 7.9). The trench does not show up in the GPR amplitude maps as it is filled with fine-grained non-reflective material that generated no radar reflections. The function of this trench can only be speculated, but one hypothesis is that it was a trash disposal area along the southern margin of the house that was periodically set on fire giving it the positive magnetic signature. That might explain why it is exactly the same length as the southern wall of the house. Sean McConnell suggested that it might be a feature similar to what he observed in Sicily where thatch roofing material was taken off a house when it had deteriorated and was placed in an adjoining trench and burned. Perhaps this trench was dug for a similar

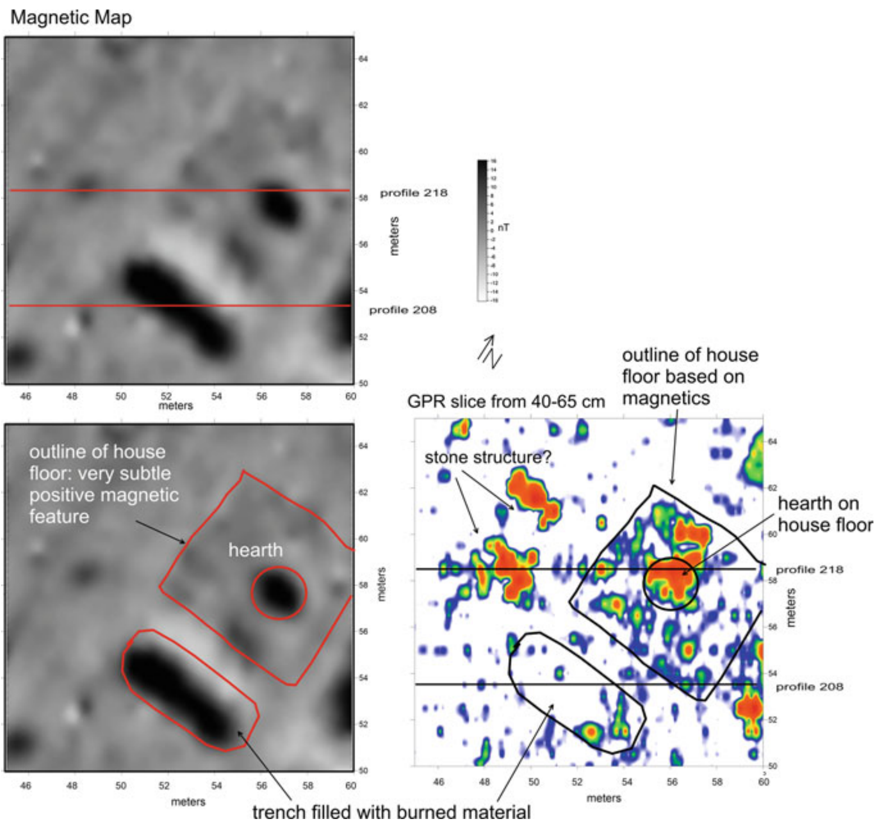

Fig. 7.8 Detailed grid within Grid 27 showing one square house with a central hearth, and an adjoining trench to the south, filled with burned material

reason, and that explains why it is almost exactly the length of the house wall. Features of this sort can possible be used as indicators for the longevity of occupation where time can be related to re-roofing events.

A GPR reflection profile (profile 218 in Fig. 7.8) that crossed the house (Fig. 7.10) displays the high amplitude planar reflection of the floor, with the central hearth. The high positive magnetic readings perfectly correspond to the location of central hearth. The remainder of the floor of this house has negative magnetic readings, consistent with being paved with locally derived clay that has a very low magnetic susceptibility. The point source reflections on the southwest edge of profile are likely the remains of a stone structure or stored stones near the house, just as seen in Fig. 7.5. This feature is also visible as two linear features of somewhat jumbled high amplitude reflections in Fig. 7.8. As this possible structure was not burned, it exhibits no substantial magnetic signature and cannot be differentiated from the natural bedrock in this area.

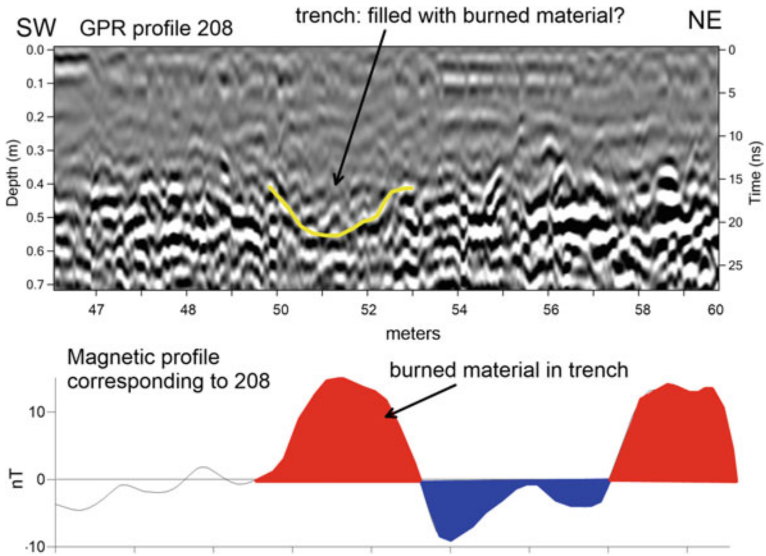

Fig. 7.9 GPR reflection profile 208 and associated magnetic readings across the trench to the south of the house shown in Fig. 7.8

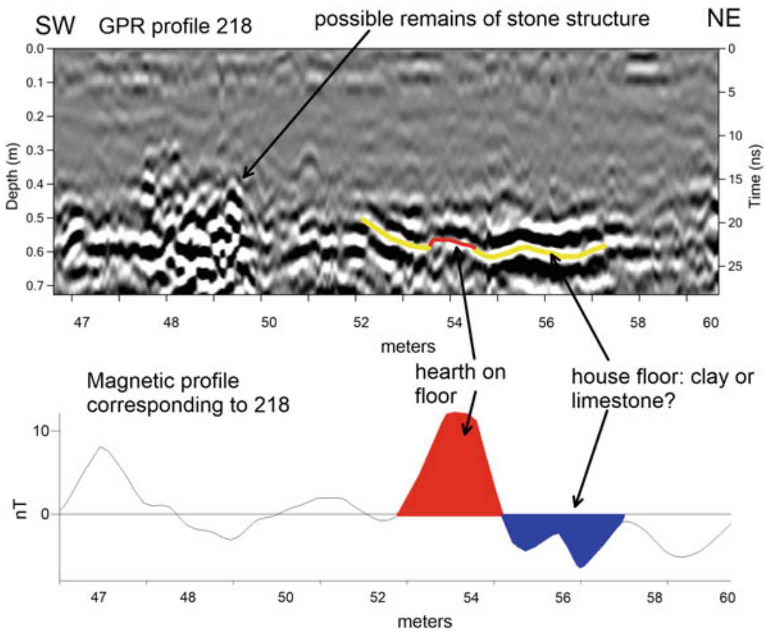

Fig. 7.10 GPR reflection profile 218 (location shown in Fig. 7.8) showing the floor of the house with a central hearth represented by a positive magnetic anomaly. The possible remains of stones or a stone structure are on the left side of the GPR profile

An area to the east of the houses discovered in Grids 25 and 27 (Fig. 7.1) is low boggy ground today, which often fills with water in the winter. A small marsh is located here most of the year, which has an island in the middle of it that was hypothesized to be the remains of a crannog. Crannogs were high status lake dwellings found across the British Isles (Edwards 1996), thought to have been inhabited in Ireland throughout most of the prehistoric period into Medieval times (Brady and O'Conor 2005; Edwards 1996). More than 1500 have been identified in Ireland alone, all of which are found associated with wet boggy areas that were in the past lakes and ponds, but then filled in over time and are often waterlogged today. Their locations in western Ireland are often coincident with where castles were constructed during the Anglo-Norman colonization and imposition of their rule. This suggests that these invading people may have in some way been trying to coopt the elite rule of the local lords, who could have resided in crannog structures (Otway-Ruthven 1980). The crannogs that have been excavated show they were constructed in various ways using both stone and timber. They were invariably built in or on the margins of lakes or marshes and contained residential dwellings and perhaps ceremonial structures.

To test the hypothesis that a crannog was located in the present marshy area to the east of the castle, Grid 32 was collected over the central island and its surrounding low areas (Fig. 7.1). A high resolution topographic map was constructed over the grid (Fig. 7.11) that illustrates two islands in the low marshy area, shown in the red and orange colors. The southern edge has been partially removed with heavy equipment in the last decades. When comparing the location of the higher areas, there is a direct spatial correlation with high amplitude features in the 25–50 and 50–75 cm depth slices. An expanded area of study was chosen within Grid 32, and all radar amplitudes were resampled and re-gridded for highest spatial resolution (Fig. 7.12).

This high resolution GPR amplitude map illustrates the floor of a structure built on this island within the marsh (Fig. 7.12). It appears oval in shape in the 50–75 cm depth slice, and is bounded on the west by what looks to be a straight stone bounding wall visible in the 75–100 cm slice. On the 50–75 cm depth slice the outer edge of this structure is defined by individual posts, which produce radar reflections. They are likely the remains of support beams placed in what was a pond or shallow wet area, prior to building the structure and which supported the building over time. The most substantial support for this structure's floor is a stone wall on the western edge, which can be seen also in the 75–100 cm GPR depth slice.

The outline of the oval structure in the GPR slice from 50–75 cm depth (Fig. 7.12) shows almost every post that was used to support it. Those posts continue into the 75–100 cm depth slice on the southern margin of the structure. The central hearth of the house can also be seen in the magnetic map, and corresponds to high amplitude radar reflections in the 50–75 cm depth slice. The magnetic map also displays the eastern outline of the structure's floor that mimics the planar GPR high amplitude feature there.

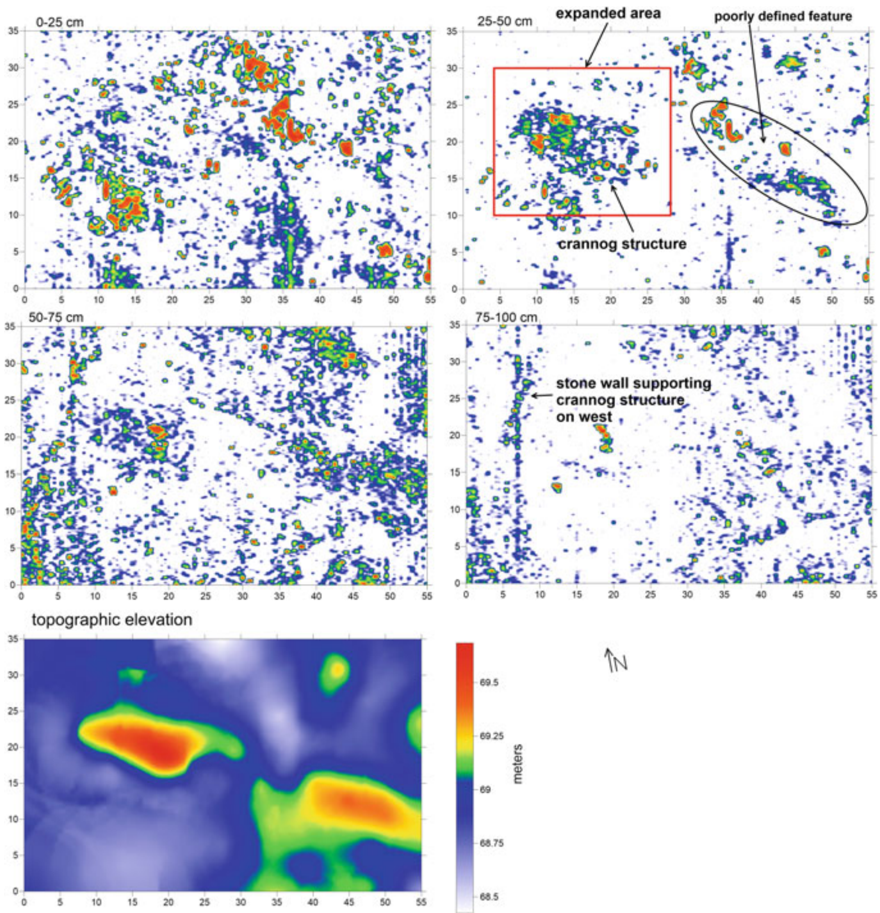

Fig. 7.11 GPR amplitude slice-maps of Grid 32, with a topographic map of the present-day surface elevations

A GPR reflection profile that crossed the crannog structure on the west shows the low amplitude pond/marsh sediments as areas of no or little radar energy reflection (Fig. 7.13). In this area of the structure (Fig. 7.12) the floor is very well defined in the GPR amplitude map at the 50–75 cm depth. The floor appears in the GPR reflection profiles as an undulating high amplitude planar reflection (Fig. 7.13).

A GPR reflection profile that crossed the eastern portion of the crannog structure also shows the floor of the house and two piles of material on that floor (Fig. 7.14). The magnetic readings associated with that floor and those features preserved on it show two very high positive magnetic anomalies. This reflection profile crossed the edges of the central hearth, and the piles are burned material along those edges. The floor on the east appears to have settled into the ground, perhaps because it was

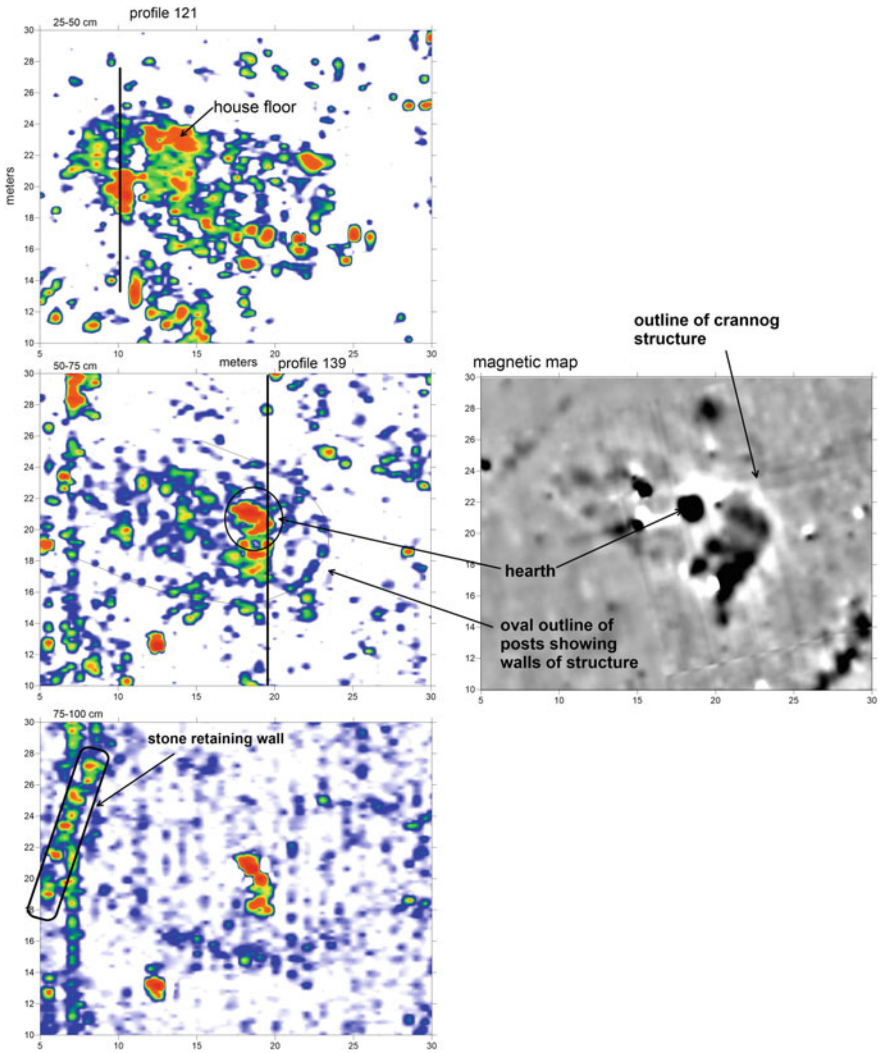

Fig. 7.12 GPR amplitude maps of the detailed area in Grid 32, location shown in Fig. 7.11

only supported there by wooden posts, unlike on the west where it that had a stone retaining and support wall.

This is the only crannog feature to date that has been discovered and published using geophysical methods. The definition of the posts, floor, stone wall, and hearth are quite extraordinary. While it is likely that it could have been discovered using magnetic surveying alone, the GPR images show the individual posts and it's supporting stone wall that are not visible with magnetic readings. The floor and the features on it are visible using GPR reflection profiles in a way that is impossible using only magnetic maps.

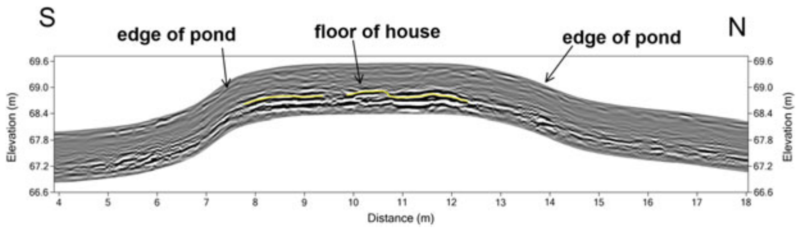

Fig. 7.13 File 121 in Grid 32 crossing the pond on the north and south of the crannog structure, and showing the high amplitude crannog floor reflection

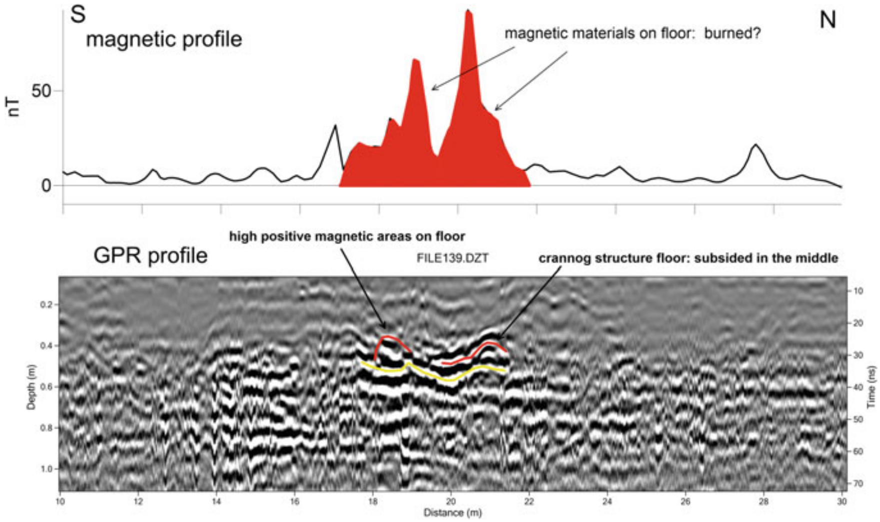

Fig. 7.14 GPR reflection profile 140 in Grid 32 with the associated magnetic readings across the crannog structure on the east, location in Fig. 7.12

7.3 Conclusions

Placing all the geophysically discovered features on an aerial photo of the pastureland to the east of the castle (Fig. 7.15) provides a way to begin to understand the buried cultural landscape of this area around the castle. In this figure the houses, roads, ditches and other features discussed in Grids 25, 25 and 32 are shown, but also others from geophysical grids not discussed here. While the ages of these features is not yet known, the houses on either side of the road leading to the castle are likely the same age as that central commanding structure in this landscape. The area to the north of the road, just east of the castle appears to have been only agricultural land in the past, with many ditches and berms, but no evidence of houses with hearths (Fig. 7.15). Unfortunately many other features are either

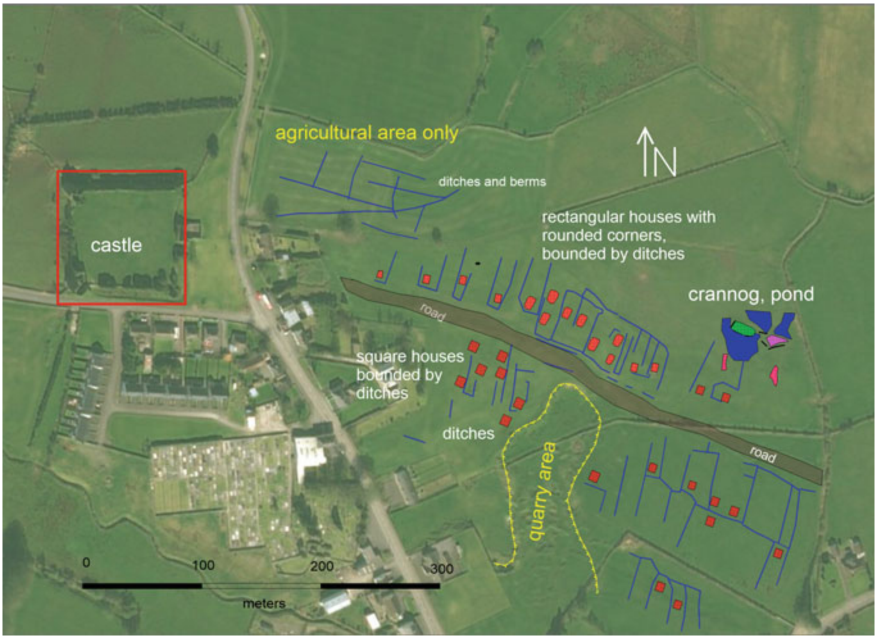

Fig. 7.15 Cultural features on the landscape discovered using GPR and magnetics east of the Ballintober Castle

located below the yards and gardens of houses in the presently occupied village of Ballintober to the south of the castle, or have been destroyed over the centuries that people have lived here. Only those preserved in the pasture land are available for study using large-scale geophysical methods.

The crannog area on the eastern edge of the study area likely pre-dates the castle, and may have been built centuries before the Anglo-Norman invasions. It is also possible that some of the houses discovered geophysically are also pre or post-castle occupation, but this can only be determined by further excavations.

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Chapter 8
Hunter-Gatherer Site in Colorado

Abstract Hunter and gather groups leave little in the way of architecture that can be directly imaged using either GPR or magnetic mapping. A site along the Colorado Front Range contains artifacts that span almost 6,000 years of time, but little was preserved in the way of architecture. Magnetic anomalies are good indicators of buried hearths or roasting pits, which also produce very subtle features in GPR profiles but almost no reflection amplitude features in slice-maps. In areas where the landscape changed dramatically over a long period of time, GPR reflection profiles can identify packages of soil and sediment that contain artifacts and other larger anthropogenic features from ephemeral occupations. The history of this area is even more complicated because the environments changed dramatically over millennia, as the nearby fluvial system degraded and at other times filled up with sediments during floods. The integration of geologically-identified strata, which can be mapped with GPR using direct correlations of known units to those that contain artifacts, is one way to place people within a landscape that changed dramatically over a long span of time.

8.1 Background to the Site

Along the Colorado Front Range, where the Rocky Mountains meet the plains is an archaeologically-rich site called Magic Mountain, which was first excavated in 1959 and 1960 by Harvard University (Irwin-Williams and Irwin 1966). Those excavations revealed a thick sequence of sediments along the north bank of Apex Creek (Fig. 8.1) just to the west of outcroppings of sandstone that produce a distinctive topographic ridge. Deeply stratified deposits range in age from about 6,000 years ago to about AD 1,000 were uncovered just to the west of this sandstone ridge. This time span encompasses the archaeological periods known as the Early Archaic through what is called the Plains-Woodland Period (also termed the Early Ceramic). Many hearths and a few human burials were discovered, with more than 3,000 diagnostic stone tool artifacts and numerous expedient tools, stone flakes, grinding stones and animal bones found within the excavated units.

L. B. Conyers, *Ground-penetrating Radar and Magnetometry for Buried Landscape Analysis*, SpringerBriefs in Geography,
https://doi.org/10.1007/978-3-319-70890-4_8

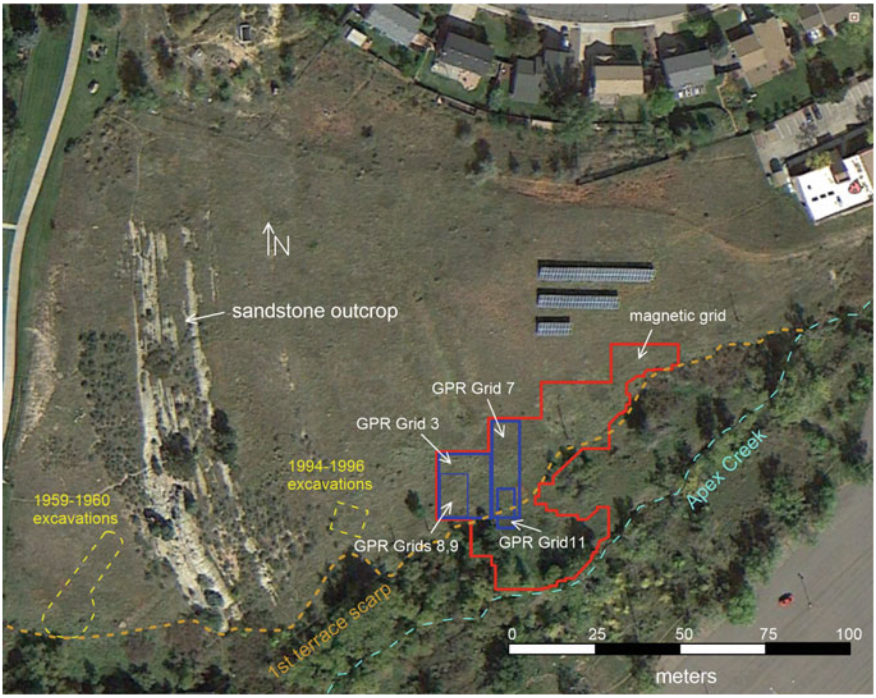

Fig. 8.1 Aerial photo of the excavations at Magic Mountain, Colorado, with the locations of the GPR and magnetic grids

Additional excavations and stratigraphic borings were conducted to the east of the sandstone outcrop (Fig. 8.1) in 1994 and 1996 (Kalasz and Shields 1997) where similar stratified units and many archaeological features were discovered ranging in age from about 1,800 to 1,000 years ago, with a few possibly older materials. Those excavations yielded artifacts that are generally younger in age than the Harvard tests to the west. The 1994–1996 excavations also yielded numerous hearths and a possible stone floor and wall of a structure. A variety of stone tools was found here along with numerous animal bones of mostly deer and bison.

The archaeological analysis of both excavation results indicate that this area of Colorado was utilized by hunter and gatherer people over many millennia. They left a variety of artifacts with abundant evidence of camping, food processing, butchering of animals and perhaps longer term semi-residential occupation. Overall this site is notable because of its wealth of artifacts spanning such a long period of time. This area of the Rocky Mountain Front Range was likely a preferred location on the landscape for people who came back to it again and again as they moved across a wider landscape in search of food and other resources. As there are few, if any, well-documented permanent dwellings here, the site is a good test for how GPR and magnetic analysis can be used to better understand subtle aspects of the material record related to peoples' adaptation to their environment.

To complicate interpretation, this site has undergone a varied geological history with periods of erosion, stability and deposition along the northern bank of Apex Creek (Fig. 8.1). This necessitates that GPR and magnetics be integrated with geological analysis of sediments and soils within which the evidence of humans is found (Conyers 2016). As the human presence was ephemeral there are no distinct houses or structures (other than the one possible dwelling that was found in the 1994–1996 tests) that might be visible geophysically, making an interpretation of this important site different than the other examples discussed in this book.

8.2 Data Collection and Analysis

In preparation for excavations conducted by the Denver Museum of Nature and Science in the summer of 2017 GPR and magnetic data were collected in locations to the east of the 1995–1996 excavations (Fig. 8.1). The magnetic data were collected by Ken and Jo Ann Kvamme from University of Arkansas. A number of GPR grids were collected after the magnetic maps in order to test the likely presence of buried features that were obtained in the early stages of geophysical data analysis during both 2016 and 2017. The overall project was coordinated by Michele Koons, Curator of Archaeology at the Denver Museum of Nature and Science in collaboration with Mark Mitchel. Magnetic data were collected with a Geoscan FM256 fluxgate gradiometer. The GPR data were acquired using a GSSI SIR-3000 system with 270, 400 and 900 MHz antennas depending on the depth and resolution necessary for the questions that were asked.

The magnetic map of the eastern study area shows a variety of magnetic dipole and mono-pole anomalies (Fig. 8.2). Some are quite strong that likely identify buried metal objects of recent origin. This area has undergone a variety of construction disturbance in the last 50 years with the burial of water lines and installation of electrical transmission poles. The more subtle features scattered through the grid mostly have ± 10 nT values, which makes them likely candidates for ancient hearths or other burned features (Kvamme 2006). In the southeastern area of the grid a number of very strong dipole magnetic features are visible, which corresponds to the modern floodplain of Apex Creek. In that area large igneous boulders and cobbles are visible on the surface, which are the surface expression of thick debris flow units that were deposited during torrential floods in the last few hundred years.

A variety of more subtle magnetic anomalies were chosen for excavation in areas farther away from the creek, many of which were positive mono-poles. These were hypothesized to be areas that were burned in the past. In one small area of the magnetic grid a subtle arc-shaped magnetic feature was visible during the initial analysis, and this area was chosen for concentrated GPR analysis (Fig. 8.1: GPR Grid 3). A number of other GPR grids were later collected in this same area using different antennas, profile spacing and transect orientations, each to test hypotheses that were generated during data analysis during the summer and fall of 2016 (GPR

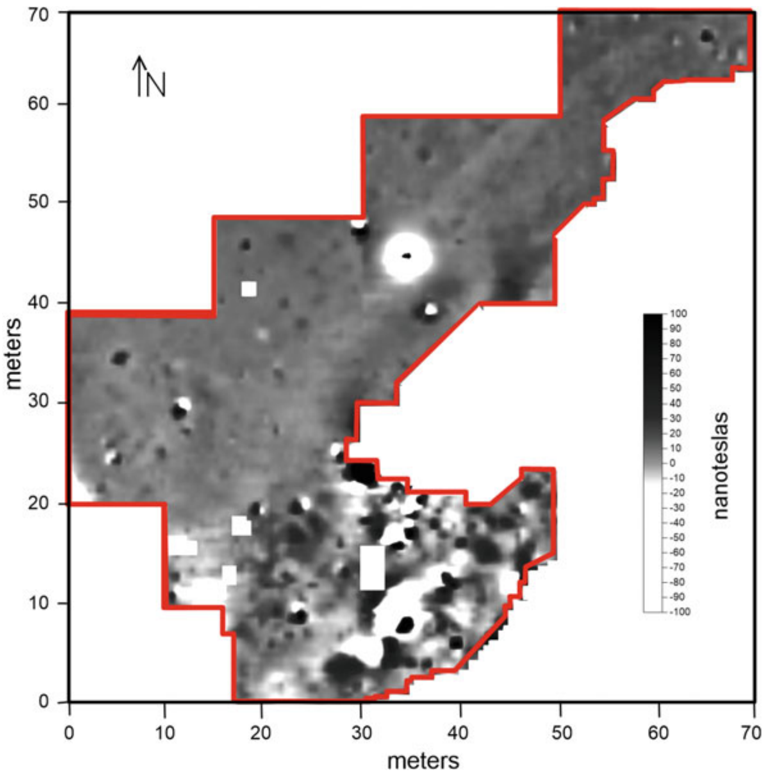

Fig. 8.2 Magnetic map of the eastern study area at Magic Mountain site

Grids 7,8, and 9 in Fig. 8.1). Grid 11 of GPR was collected during 2017 to test ideas related to one excavation where new and complex geological features were uncovered.

The subtle arc-shaped feature discovered in the magnetic map was surveyed in GPR Grid 3 using the 400 MHz antennas (Fig. 8.1). In that survey one horizontal planar reflection was visible in all the western portions of the GPR profiles between 30 and 40 cm depth, which was wistfully hypothesized to be the floor of a possible semi-permanent living structure. The area where this planar horizon was found were plotted on a GPR amplitude map, with the point-source hyperbolic reflections (thought to have been generated from buried stones) as dots (Fig. 8.3). When these are placed on the magnetic anomaly map, there is little correlation between the presumed stone reflections and the positive magnetic anomalies. The planar reflections are all concentrated in the western area of the grid, and generally cluster, but do not exhibit a pattern consistent with of any known prehistoric structure from this area of Colorado. In addition, the stone GPR reflections are not found in locations where they might be walls or associated with a floor, which also tended to refute the buried structure hypothesis. Some of the point source reflection locations are generally associated with magnetic anomalies, but many are not.

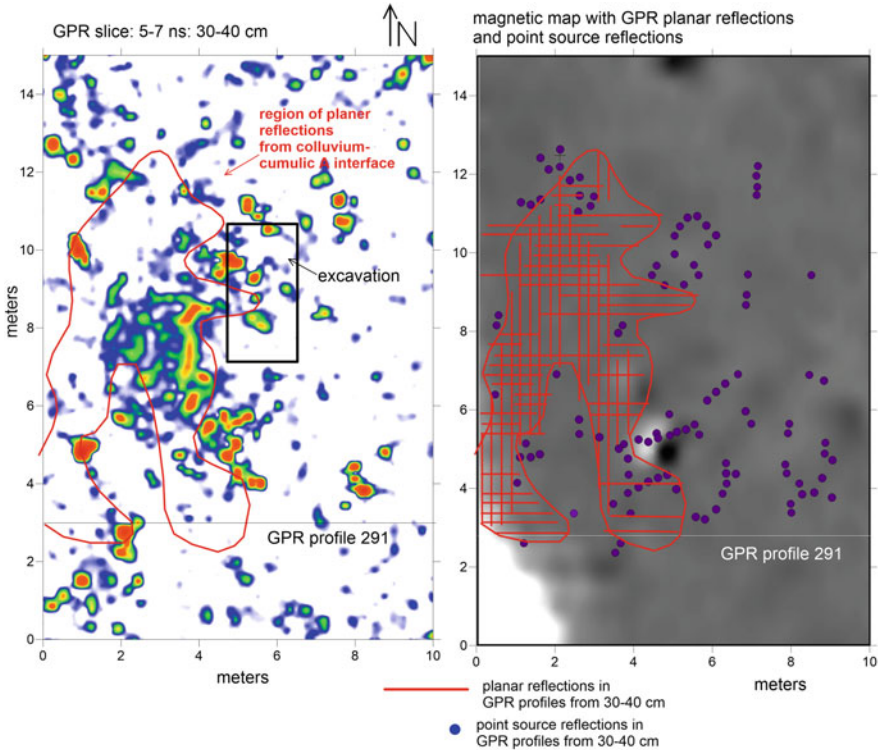

Fig. 8.3 GPR amplitude map and magnetic map with the superimposed location of planar and point-source reflections visible in GPR reflection profiles. An interpretation of data from both 400 and 900 MHz grids is shown here, plotted within the confines of GPR Grids 8 and 9. The GPR amplitude map was constructed using only 400 MHz reflection data

An excavation was then placed in the middle of this concentration of planar reflections (Fig. 8.3). The geological units uncovered show a surface soil underlain by a layer of reddish clay-rich soil that was highly disturbed and has a sharp basal contact (Fig. 8.4). That unit is the disturbed remains of a Bt soil horizon (subsoil) that had been recently excavated by heavy equipment from a trench still visible nearby and dumped here. This unit is therefore a “spoil” deposit and has no significance to the study. Underlying the spoil layer is a sandy unit containing a few angular pebbles that is a slope-wash/colluvium unit, which was washed or slumped into this area from the small drainage to the north and from the sandstone outcrop just to the west (Fig. 8.1). Within this sandy unit a number of artifacts were found and many stone tool flakes, all of which show that people were utilizing this area of the landscape. Below the slope-wash/colluvium unit, at a very sharp contact, is a reddish well sorted fluvial sand, with abundant organic material. This unit is termed a cumulic A horizon (Birkeland 1984) and denotes an environment close to the creek that was periodically receiving sand deposition during floods but also had

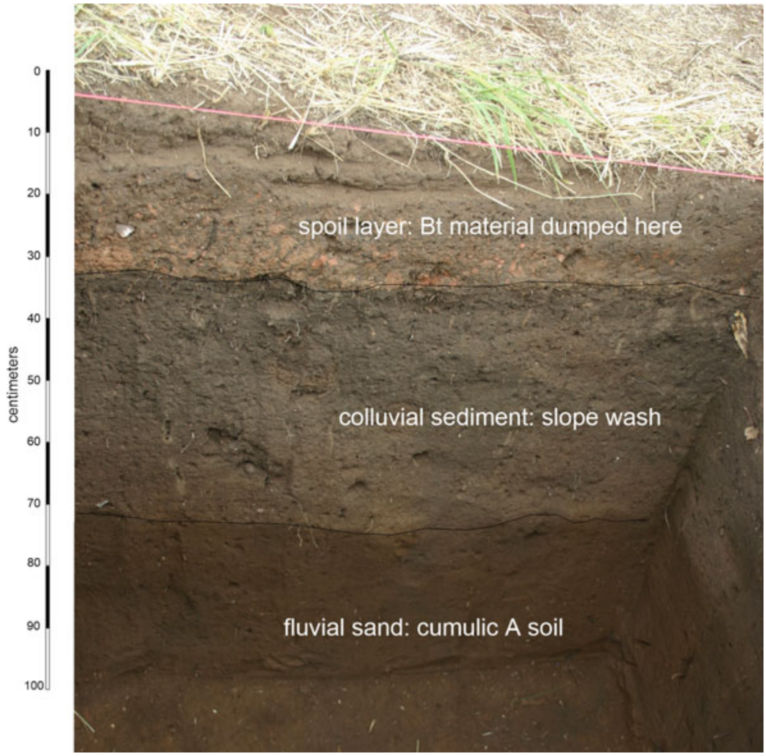

Fig. 8.4 Geological units in the western part of GPR Grid 3 showing the layers visible in GPR profiles

abundant vegetation that provided organic material, which became an A soil horizon. These types of A soil units are often sandy and "over-thickened" as sediment was being periodically introduced into the area while soils continued to develop. The sandy cumulic A unit shows that Apex Creek was flowing at or near this elevation in the past, which is about 2.3 m higher than it does today. The layer contains artifacts and bones throughout. At the time people utilized this area it was the location of food preparation and cooking as stone tool artifacts and grinding stones for food processing with charcoal from fires found throughout. The area on the landscape where these activities occurred was on the bank of the creek where water could be obtained nearby, but which periodically flooded during spring runoff of melting snow from the nearby mountains and perhaps summer thunderstorms. For much of the warmer times of the year this area had abundant vegetation growth, and soils built up over the centuries, even as it continued to be periodically flooded.

The contact between the sand and the overlying colluvium unit is the interface that produced the distinctive planar reflection visible in the GPR profiles from this area of the site (Fig. 8.5). It was not a floor, as originally hoped. When GPR profiles across the area where the planar reflection was visible are corrected for surface

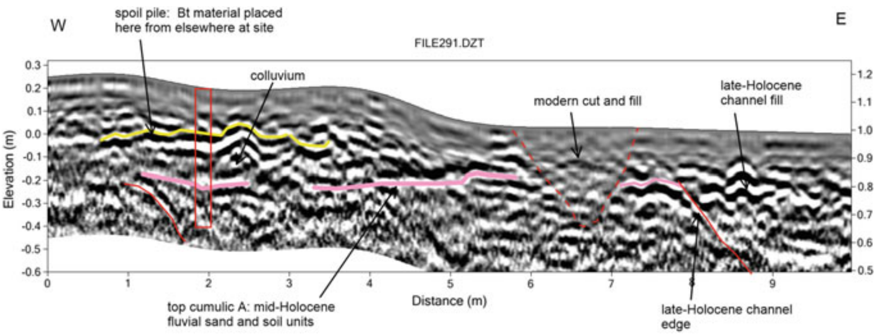

Fig. 8.5 Topographically corrected GPR reflection profile (location in Fig. 8.3) showing the geological layers from the excavation in GPR Grids 3, 8 and 9. Data were collected with the 900 MHz antennas

topography, and the sediments and soil units discovered in excavations are correlated to the radar reflections, a three-dimensional analysis is possible (Fig. 8.5). The spoil deposit is visible as a near-surface layer within the colluvial sediment package. A distinctive contact between the colluvial sediment and the underlying fluvial sand is the interface that had produced the distinct planar reflection seen in GPR reflection profiles. At this contact, which is likely an unconformity, the environment at this location changed from creek-side (within a very narrow floodplain of the channel) to higher ground. This occurred as the creek incised to a lower elevation perhaps as a result of a major erosion event, or perhaps a gradual climate change that cause the channel to degrade. People continued to seasonally live here and perform basic tasks such as food processing and cooking, with the creek flowing at a lower level and a little farther away than it had in the past. The area around Grid 3 continued to receive some sediment, which accumulated as gravity-deposited colluvial debris and slope-wash units. As these units are formed by sediment moving downslope during rainstorms or snow melt episodes, much of the artifacts within this unit are likely out of place, having been moved by geological forces to their final burial locations.

The GPR amplitude slice-map that includes the contact between the lower fluvial/cumulic A horizon and the overlying colluvial/slope wash layer exhibits high amplitudes in the same area where the planar reflection created from this contact was visible in GPR reflection profiles (Fig. 8.3). The high amplitudes on this map are the product of the chosen slice (30–40 cm) that includes the sharp contact and also because at this depth the units contain many stones that produce reflections. Some of those stones were likely brought into the area by people who performed many activities during the time this small area was within the floodplain, and also as the environment changed to a more upland location after the creek had eroded downward to a new level.

The excavations conducted within this grid (Fig. 8.3) discovered a variety of slightly burned stone features composed of fragments of grinding stones, which were preserved close to the contact of the two prominent geological units visible in the GPR maps and profiles (Fig. 8.6). Many smaller stone artifacts were found near these stone features, all of which indicate that people were cooking, processing food and using and sharpening tools here. Over time the living surfaces on which people lived and worked were periodically buried and preserved by slope wash and colluvium. The GPR analysis in this grid was capable of identifying the horizontal contact, which was initially misinterpreted as a floor. The overall distribution of the planar surface and the stones were a hint that the floor hypothesis was incorrect, but this could only be confirmed when the layers of soil and sediment were exposed and correlated directly to the visible GPR reflections. When this was done, an environmental analysis was possible for this area of the ancient landscape in three-dimensions. The concentration of individual stones visible as point-source hyperbolas from the depth, where we now know that many artifacts were preserved, may be showing prehistoric activity areas, but this has not yet been confirmed by excavation analysis. The magnetic mapping in this area was only capable of finding the slightly burned areas.

In much of the eastern area of the magnetic grid (Fig. 8.2) only weak monopole magnetic anomalies are present with a few very distinct dipoles that were produced from modern metal. Five of these subtle magnetic positive anomalies were chosen for excavation, and all five revealed buried burned prehistoric features including hearths and earth ovens. None of these discovered features were immediately visible in either GPR amplitude maps or reflection profiles and the initial GPR

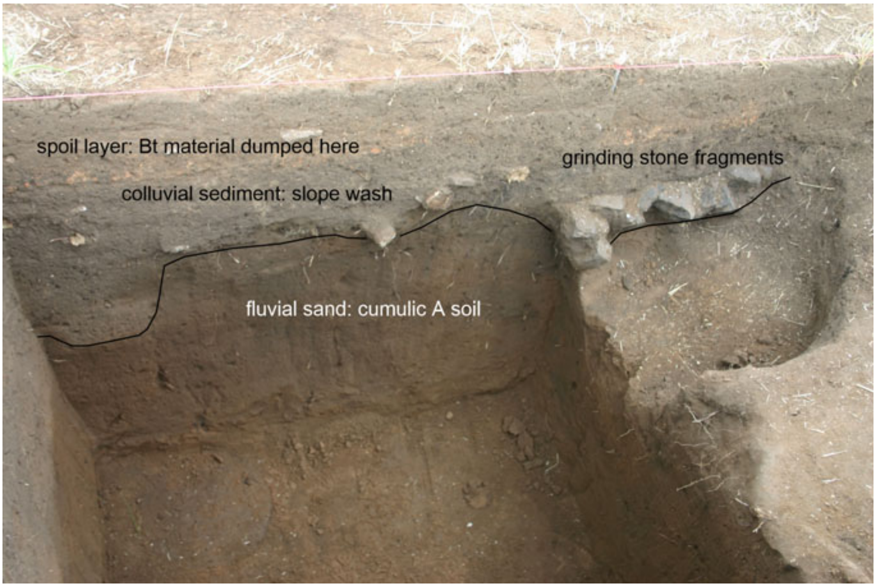

Fig. 8.6 Grinding stones and a slightly burned unit along and just above the contact of the cumulic A soil within the fluvial sand, with the overlying colluvial/slope wash sediment

interpretation of those areas in GPR Grid 7 (Fig. 8.1) were considered too subtle to be large archaeological features, based on the small size of the high-amplitude reflections.

In the excavations conducted in GPR Grid 7 and other areas to the east, which were not surveyed with GPR, a distinct Bt soil horizon that is reddish brown in color was uncovered (Fig. 8.8). It is clay-rich and contains a minor amount of calcium carbonate found from about 30–40 cm. In this area of Colorado soil units of this sort indicate landscape stability over a good deal of time (many hundreds or thousands of years), which allowed clay and some carbonate to accumulate in the soil horizon below the surface A zone (Birkeland 1984). The burned features discovered in excavations were incised into this Bt horizon, or created directly on it. They are extremely difficult to see in GPR amplitude maps or reflection profiles and what subtle GPR features are mapped can be easily confused with random stones found across this landscape. The burned features can be identified only using magnetic mapping.

Once these buried burned features were exposed and could be analyzed, the GPR profiles and magnetic readings were studied to determine what geophysical signatures were denoting these subtle but common prehistoric archaeological features. One profile across what was found to be a buried hearth shows a very subtle mounded layer surrounded by a unit that was incised into the Bt soil horizon (Fig. 8.7). The magnetic values that correspond to the GPR reflection feature show a positive magnetic signature, with a very subtle negative deflection on the north. The geological units here show that this area of the site was a stable living surface

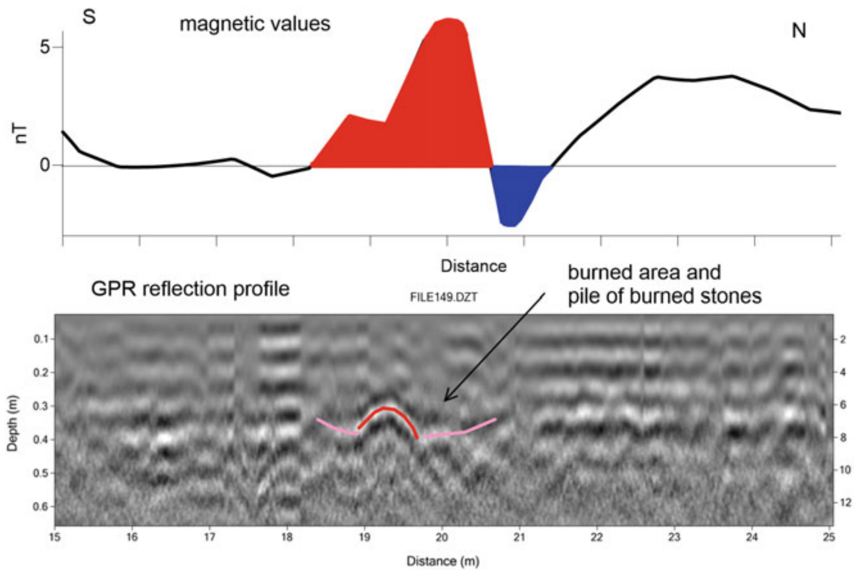

Fig. 8.7 Representative GPR profile and magnetic values of a burned area with a pile of stones from an earth oven or possible hearth in GPR Grid 7. Data collected with the 400 MHz antennas

for a long period of time where people constructed a fire pit, which could have been a small baking oven that included fire altered stones (Fig. 8.8). In other excavations nearer the creek to the south these same kinds of features are visible using GPR profile analysis, but in that area a thin fluvial sand unit overlies the burned features. This shows that closer to the creek the land was still subject to flooding during high water events.

An area about 10 m north of the modern Apex Creek floodplain was chosen for excavation as it showed no magnetic features at all. It was chosen as a “control” point to determine the nature of buried layers that produce no magnetic anomalies. This area later became Grid 11 (Fig. 8.1) where 270 MHz antennas were used to collect GPR reflection data.

The magnetic map of Grid 11 shows a few subtle magnetic anomalies, and one distinct dipole anomaly in the northern half of the test area (Fig. 8.9). Two test excavations were placed in an area of no positive or negative magnetic readings in the middle of the grid. The southern half of the grid shows many very strong positive and associated negative magnetic features. The ground surface in this area is covered with large igneous boulders and cobbles derived from the Precambrian granite and gneiss rocks of the Rocky Mountains, which rise dramatically just a kilometer or so to the west. It is likely these were deposited recently during torrential floods that generated debris flows capable of moving these large rocks into this location of the floodplain.

Fig. 8.8 The burned feature, which is likely a hearth, cut into the Bt soil horizon and overlain by a thin layer of fluvial sand with interbedded weak A soil horizons. This burned feature appears as a subtle GPR reflection from the stones, and the magnetic anomaly indicates burning occurred here (Fig. 8.7)

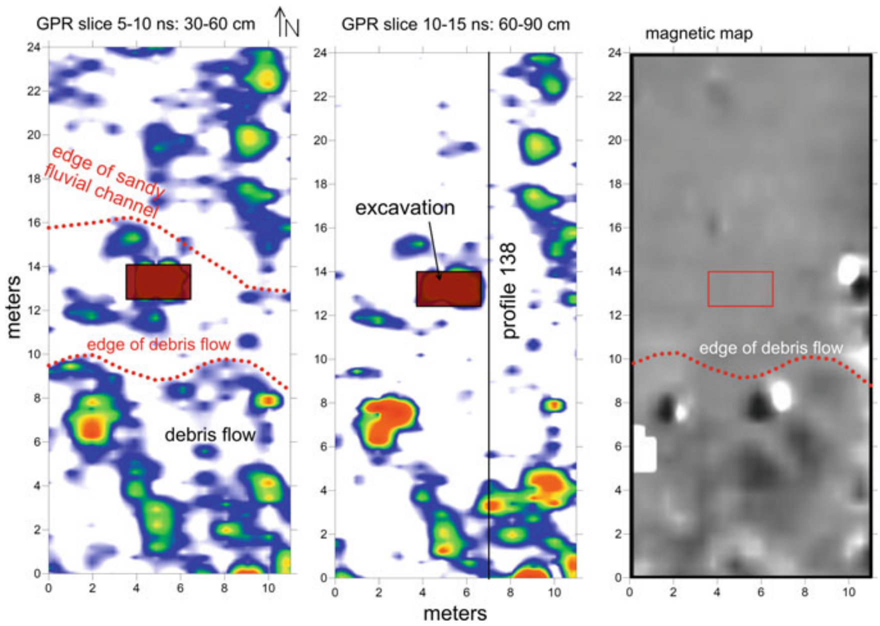

Fig. 8.9 GPR amplitude maps and the magnetic map of Grid 11 showing how both methods can readily show the edge of the debris flow deposits in the southern portion of the test area. Data collected with 270 MHz antennas

A 1 × 2 m excavation in Grid 11 (Fig. 8.9) was dug to about 1.2 m depth, uncovering fine-grained sand mixed with abundant organic material in what is a very thick cumulic A horizon. The sand deposited here is fluvial in origin and shows that this area of the site was receiving sediment from the watercourse often during spring snow melt events or thunderstorms, when the creek was flowing outside its normal channel and depositing sediment along this narrow floodplain. At other times the area was heavily vegetated and A soil formed, forming a very thick cumulic A horizon. Scattered stone tool flakes were found throughout this sand, showing that people were working or living nearby, but no other archaeological features of interest. This cumulic A horizon was found to be sitting on a coarse cobble layer, which was an earlier fluvial deposit or debris flow.

A 270 MHz GPR reflection profile within Grid 11 readily displays the geological units in this test area (Fig. 8.10). The southern portion of the grid, where the strong magnetic anomalies are visible, exhibits many channel units when viewed in profile. Thick cobble layers appear in profile as channels, and the northern edge of these debris flow units is readily apparent. The edge of these channel-fill debris flows occurs just a few meters south of the excavation (Fig. 8.9). To the south of this channel edge all previously deposited cumulic A deposits, which were visible

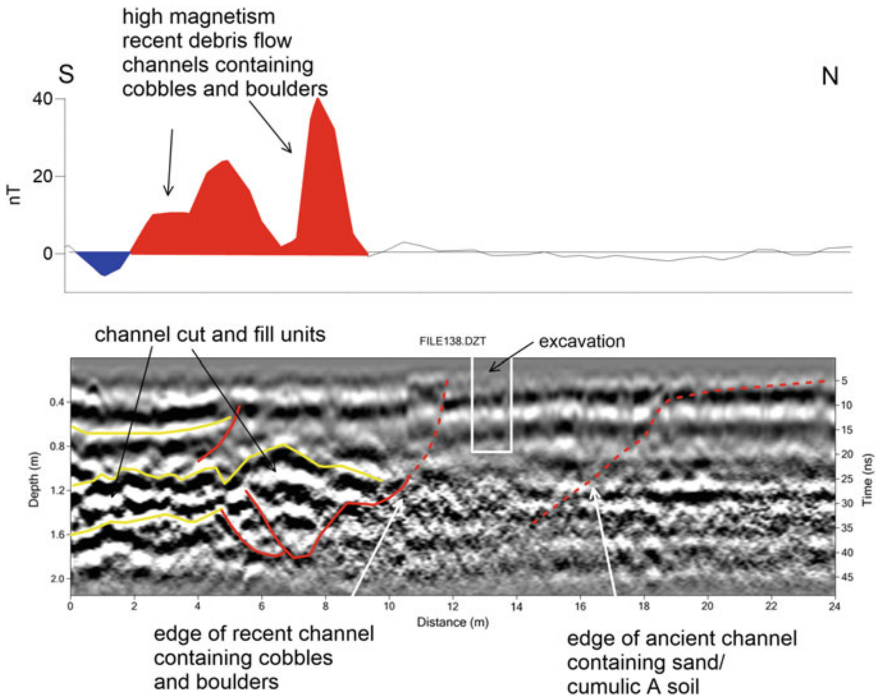

Fig. 8.10 A representative 270 MHz GPR reflection profile in GPR Grid 11 (location shown in Fig. 8.9)

in the excavation, have been eroded away and washed downstream (Fig. 8.10). The channel edge is also readily visible in the magnetic map, with the debris flow units being the area of high positive and associated negative anomalies produced from the recently deposited igneous rocks.

Just a few meters to the north of the excavation the thick cumulic A/fluvial sand was found to pinch-out upslope along the edge of what was a channel. Excavations just to the north of Grid 11 revealed the Bt horizon preserved there at only 35 cm depth (Fig. 8.8). This shows how dramatically the ancient environments changed in a short lateral distance. Both the GPR and magnetic analysis in Grid 11 is indicating that this general area near the present creek underwent notable landscape changes during the last 1,000 years or so. During the earlier part of this millennium-long time span the floodplain of Apex Creek was wider and the creek was actively depositing fine-grained sand. North of this bank of this creek (somewhere north of the excavation in Grid 11) was a stable surface, except for very rare flood events, thin deposits of which are visible as a sand layer in Fig. 8.8). Along that northern bank of the creek where the landscape was stable the Bt horizon and an overlying A soil unit continued to develop at only 35 cm depth, and people used this area for cooking and food processing. The nearby creek and floodplain to the south were

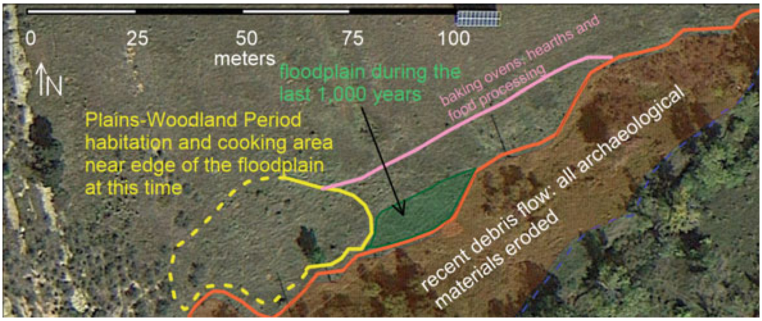

Fig. 8.11 Interpretation of the landscape and changes in the environment at the Magic Mountain site east of the sandstone outcrop

probably used for obtaining water and for some ephemeral activities, as seen by the rare but still prevalent artifacts in the excavation conducted in Grid 11.

Once the geological units were identified in Grid 11, and their significance to the landscape evolution of the area understood, the geophysical maps could be used to project ancient environments to the east and west (Fig. 8.11) and determine how they changed over time. The magnetic map in particular is useful to show the extent of the recently deposited debris flow as it appears as very strong positive and negative anomalies. The ancient hearths are visible in the eastern portion of the study area directly abutting the debris flow units (Fig. 8.11), indicating that the floodplain cumulic A unit visible in the excavation in Grid 11 was likely eroded in that direction (Fig. 8.1). Only the higher elevation stable uplands to the north contain evidence of cooking and food processing.

8.3 Conclusions

The integration of the two geophysical methods accompanied by an analysis of geological strata, and the archaeological materials found throughout can produce an environmental history of this area and show how the landscape changed during the time that people used this site. To the west of the study area the Harvard excavations (Excavation 8.1) shows that people were living in that part of the Apex Creek drainage perhaps as early as the Early Archaic Period, about 6,000 years ago. Those deposits are likely preserved there because that part of the landscape was "buttressed" by the sandstone outcrops, which deflected flood waters from the creek bank on the north. Early Archaic people also probably lived and worked to the east of the sandstone ridge, but those deposits have been removed by erosion.

In the study area to the east of the sandstone outcrop (Fig. 8.1), the earliest preserved occupational levels are from the Plains-Woodland Period beginning about 2,000 years ago. Only a small area just to the east of the sandstone outcrop contains the well layered soil and sediment units from this time, found in the 1994–1996 excavations and visible in some 2017 excavations and the GPR maps in the vicinity of Grid 3 (Fig. 8.1). During the time that people were utilizing that area for food processing and cooking, the floodplain of the creek was higher in elevation than today. The excavations show that cooking and food processing occurred along and perhaps within the floodplain around Grid 3. Later the creek degraded to a lower level, and a new floodplain was formed, whose deposits were found in the excavation in Grid 11 (Fig. 8.9). It is likely that during that degradation event some of the floodplain deposits south of the Plains-Woodland habitation area were eroded away, as the highly magnetic debris flow unit impinges directly on the thick older deposits found in Grid 3. During the Plains-Woodland time period people probably built fires and processed and cooked food in the stable high areas of the eastern part of the site, but those burned features are not yet firmly age dated.

The new floodplain, which likely started to form about 1,000 years ago deposited fine-grained sand, visible in the excavation in Grid 11 (Fig. 8.1). At that time people continued to use the higher elevation stable part of the landscape for cooking and food processing, and their hearths are visible using the magnetic map (Fig. 8.11). They also performed some activities in the floodplain, but artifacts there are much less dense than in the upland areas where their hearths and other activity areas are covered by slope wash and colluvial sediments.

Only recently have very large debris flows deposited boulders and cobbles in the floodplain of the creek (Fig. 8.11). That event, or multiple events, which emplaced those large rocks appears to have eroded and removed much of the earlier floodplain deposits and perhaps some of the cooking and food processing sediments along the northern bank of the creek to the east.

While human occupation of the ancient landscape is not nearly as well-defined geophysically as some of the other examples discussed in this book, with a concerted effort to use each method's strengths, and an integration of that information with the geological strata, important conclusions about the evolution of this landscape can be made. This area along the Colorado Front Range has been a place that drew hunter-gatherer people for thousands of years. It was protected from north and northwest winds by the sandstone outcrop and the natural slope of the ground to the south that gave it maximum solar radiation. This suggests a likely cold weather usage of this area by these mobile hunter-gatherer people going back to the Archaic Period. They chose stable ground for many of their activities, and their hearths and other features are still preserved on that living surface. Over time the creek cut downward and the floodplain in some cases widened or narrowed in this dynamic fluvial setting. The periodic visitors to this area no doubt chose some areas of this landscape for certain activities, sometime on the higher stable ground, but perhaps also in the floodplain. Much of the activities that may have taken place in the floodplain have been removed by subsequent erosion, and only pockets of sediment and soils containing their artifacts are still preserved.

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Chapter 9
Conclusions

Abstract Large scale GPR and magnetic maps of the near-surface need not be used as only discovery and exploration tools, which has traditionally been the case. As the two techniques are measuring and displaying very different aspects of buried natural and cultural landscapes, they can be used in conjunction to study both human and environmental changes over time. In two examples (Colorado and Connecticut) the magnetic maps were capable of displaying areas of burning, or were in some areas cluttered with so much surface metal that cultural feature definition was impaired. When those magnetic measurements were used to help interpret geological and architectural units visible with GPR, the utility of using both in conjunction was proved. Other examples in England and Ireland produced excellent maps using one or the other method, but were complemented when the two datasets were used in conjunction. The method employed here is to use GPR and magnetics in combination concentrated first on understanding small areas by interpreting two-dimensional profiles as a way to recognize what about the ground was being measured by each technique. When that was accomplished an analysis of the larger landscape-sized sites was possible.

9.1 Interpreting GPR and Magnetometry Data Sets in Different Areas

The term landscape has been used in a number of ways here, both to indicate the natural landscape, which would include environment factors, and the cultural landscape that is the human-built or modified aspects of the archaeological record. Buried natural landscapes can be readily understood using GPR, as it has the ability to define strata that are good indicators of units that were deposited as sediments when conditions were unstable and soils that formed when the ground was stable. An understanding of the dramatic environment changes that occurred over millennia was possible at the Magic Mountain Site in Colorado in this way. People's use of fire for cooking and other activities were discovered with magnetic analysis, within the GPR-defined environments. Magnetic analysis when used with GPR can

L. B. Conyers, *Ground-penetrating Radar and Magnetometry for Buried Landscape Analysis*, SpringerBriefs in Geography,
https://doi.org/10.1007/978-3-319-70890-4_9

often indicate the composition of buried geological units, as was shown with the complex layers in the Connecticut example. Most often magnetics mapping in the upper layers of the ground is more conducive for defining human changes to the environment such as burning events, ditching and mounding of ground, and post-abandonment robbing of stones. These types of human modification of the environment are particularly important in placing humans within the broader landscape, and often can be used to illustrate cultural changes over time.

In this book I have tried to give examples where only one of these geophysical methods applied to a complex buried site would yield only a partial picture of the natural and cultural features of interest. This is especially so when studying aerially extensive features, when the use of GPR or magnetic maps produces a dizzying array of features. Those large-scale maps, some of which are presented here, can be hugely important as they can be used almost like "street maps" of cities today. That was much the case for the England and Ireland examples, as they were outlining buildings, roads and other cultural features in a built environment that well preserved under the ground. In those examples details from the GPR profiles when compared to the magnetic readings in two-dimensions showed that these street maps were much more complicated and interesting than initially thought. At those sites specific readings with magnetics, or geological or anthropogenic units that were defined with GPR could be used to identify and interpret very specific features of the cultural landscape such as floors, hearths, walls and ditched and berms. Those features yield important clues to who lived where and what they may have been doing in their lives (as in the case of the Ireland example).

Much of the interpretations presented here are preliminary, and await decades of excavations and other subsurface testing. While they may be preliminary, they are still well substantiated because the two methods were used in conjunction and therefore produce two very different analyses of the buried features that helped with interpretation and definition.

At the Magic Mountain site in Colorado and the Hollister site in Connecticut, the initial magnetic mapping produced little in the way of features that could be readily understood. In Colorado the magnetic anomalies were all shown after excavation to be buried burned features, which documented human activities in small areas. When those were excavated, the surrounding sediments and soils provided even more evidence of landscape change, using traditional geological analysis. Those exposed units could then be correlated directly to the GPR reflections and a more aerially extensive analysis of the site could be done employing both methods. In Connecticut an initial interpretation of the magnetic map showed only recent buildings and metal trash, with some intriguing geological units in one small area. Hidden in those magnetic readings were very important differences in the magnetic susceptibility of the buried units and features, which could be compared directly to the GPR reflection profiles where much more could be seen and understood. At those two sites GPR provided the bulk of the data from which to study the buried landscapes, but the magnetic information was crucial in understanding the nature of buried units and human-produced features within those units.

As both GPR and magnetic gradiometry are now capable of collecting large aerially extensive datasets, there is no excuse for not employing both when there is the possibility of studying the human and natural landscape. When used in conjunction these two methods can be much more than tools for exploration and discovery of buried remains. Instead they can place humans within complex built and natural landscapes in ways that was impossible only a decade ago.